INVESTIGATION OF SOLIDS LOSS AND EROSION PROCESS ON COMPOST BLANKETS USED FOR SOIL EROSION CONTROL UNDER CONCENTRATED FLOW CONDITIONS

by

XIANBEN ZHU

(Under the Direction of Lawrence M. Risse)

ABSTRACT

Although a variety of composts have been effective in reducing soil erosion from the impact of rainfall, the response of compost to concentrated flow and compost failure due to erosion, were largely unexplored. This dissertation examined the solids loss and the process of rill erosion on compost blankets subjected to concentrated flow under both laboratory and field conditions. Some erosion of yard waste compost in the laboratory was minimally similar enough to follow the shear stress equation used to describe soil erosion. Nevertheless, an additional equation was necessary to describe all the compost erosion processes observed. For the first time, this investigation made systematic observations of the formation of micro-dams in compost that are often observed *ad hoc* during rill erosion and failure of some compost applications. Micro-dams formed and truncated rill formation in erosion control compost in both the laboratory and field, and in yard waste compost on field plots, hampering estimation of shear stresses. Thus, the semi-empirical shear stress equation could not describe all compost erosion over the wide range of test conditions. This investigation derived an empirical equation based on laboratory erosion and tested the regression with field observations. The resulting regression equation better represented compost erosion both in the laboratory and in the field compared to the shear stress equation for soil erosion. The use of the Buckingham PI Theorem to derive dimensionless groups of parameters for the regression ensures that future observations can more easily generalize the empirical equation derived by this study.

INDEX WORDS: *Best management practice, Buckingham PI Theorem, Compost blanket, Concentrated flow, Dimensional analysis, Erosion, Micro-dam, Nonpoint source pollution control, Rill erosion, Shear stress, Soil erosion, Solids loss*

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XIANBEN ZHU

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XIANBEN ZHU

Major Professor: Lawrence M. Risse

Committee: Steven C. McCutcheon
Ernest. W. Tollner
Todd C. Rasmussen
Larry West

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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DEDICATION

To my parents, Yaoyang Zhu and Qunying Li, who gave me a life. To my wife, Hongbo Ma, and my daughter, Alice L. Zhu, who changed my life.

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CHAPTER 1

INTRODUCTION

Compost is produced by a controlled aerobic process in which microorganisms convert organic materials in the presence of suitable amounts of moisture and air into decay products similar to soil humus (Haug, 1993). Also useful to recycle a variety of organic waste materials as feedstock, composting has become a principal method of waste reduction, disposal, and reuse. The final product is free of pathogens and plant seeds and stable enough to allow beneficial applications to land. The high nutrient and organic content of compost has been used by farmers for centuries as a soil conditioner and an amendment to improve soil fertility and growth of vegetation (Haug, 1993). With the passage of the United States Intermodal Surface Transportation Efficiency Act of 1991, which encouraged the use of environmentally safe compost along highway rights-of-way, state departments of transportation began in earnest to investigate compost use (Kirchhoff *et al.*, 2002). In 1997, 34 states in the U.S. reported feasibility tests or routine use of compost on roadsides in one or more applications, including as a soil amendment, as mulch, for erosion control, and in other applications (Mitchell, 1997). Within 4 years, 31 states specified compost use in highway construction--26 for soil amendment, 11 for landfill backfill mixes, and 9 for erosion control (Alexander, 2001). The next year, American Association of State Highway and Transportation Officials published guidance on compost applications for erosion control (Alexander, 2002). Soon the United States Environmental Protection Agency (USEPA, 2006) recommended compost as a best management practice for erosion control and storm water management.

Although a variety of composts have been effective in reducing soil erosion from rainfall, some green composts allowed more solids loss on a sloping clayey sand under a simulated rainfall than the soil without a compost cover (Xiao and Gomez, 2009). Others have observed the erosion of compost under natural rainfall as well. Figure 2.1 in this dissertation shows evidence of erosion occurring on compost in the field.

To prevent the inadequate specification of blanket thickness or even misapplications, this study quantified the erosion resistance and stability of compost. This dissertation determined the amount of rill erosion on compost under concentrated flow. The two major parts of the dissertation are first an investigation of laboratory and field compost erosion, and second the development of an equation that related solids loss from compost to the characteristics of the compost and application sites. Chapter 2 is a literature review of compost characteristics, general uses and special use as soil erosion control practice. It also traces the origin of the shear stress equation usually used to describe soil erosion, and introduces the Buckingham PI Theorem for dimensional analysis. Chapter 3 reports on rill erosion rates for yard waste compost, erosion control compost, and the reference Cecil soil on four slopes, each subjected to four rates of concentrated flow. This investigation estimated and compared the feasibility of using the shear stress equation to describe rill erosion occurring on the reference Cecil soil, the yard waste compost, and the erosion control compost. These measured erosion rates and shear stresses were used to determine critical shear stresses and erodibility using the shear stress equation developed for soils. Chapter 4 reports on the rill erosion of yard waste compost, erosion control compost, and a reference loam soil on a 12.5 percent slope subjected to four rates of concentrated flow. This study also investigated and compared the erosion processes on those three types of material.

Chapter 5 presents three independent dimensionless groups of important variables integrated into a general equation relating those three groups using Buckingham PI Theorem of Analysis (Buckingham, 1915; Murphy, 1950). Chapter 6 provides conclusions.

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CHAPTER 2

LITERATURE REVIEW

This overview covers the following topics: characteristics of compost, effects of applying compost on soil, general uses of compost and specific uses for erosion control; available guidelines for compost used for erosion control, and the need to describe erosion from compost. Subsequent chapters distill some of this review on specific topics.

Characteristics of Compost

Compost is the product of microbial recycling of organic matter in the presence of suitable amounts of air and moisture into a humus-like product (Haug, 1993). Feedstock for the composting process may include trimmings from landscaping vegetation, crop residues, paper pulp and fiber, food scraps, wood chips, municipal solid waste, manure, wastewater treatment sludges, or other organic wastes. Composting of organic wastes has become a principal method of waste reduction, disposal, and reuse. The final product is stable, free of pathogens and plant seeds, and can be beneficially applied to land, especially disturbed landscapes with poor quality soil. Composts have been used as a substitute landfill liner (Benson and Othman, 1993), as an alternative soilless plant growth media (Freeman and Cawthon, 1999), as a soil amendment and conditioner, as a fertilizer, for erosion control, and for reducing herbicide use (Mitchell, 1997).

To use compost, the material must be characterized both physically and chemically to assure meeting the requirements of the application. Of particular concern are metals content, organic stability, organic matter content, cation exchange capacity, nutrient content, pH, bulk density, moisture content, and particle size distribution. While the variability in compost characteristics is quite dramatic and influenced by type of feedstock, season, region, and process controls, Kirchhoff *et al*.(2002) reported that most compost has a pH in the neutral range, organic matter content in the 30 percent to 60 percent range, moisture content of 30 percent to 50 percent, and higher values of nitrogen, phosphorus, potassium, and salts than typical agricultural soils. Some compost (especially compost derived from municipal solid wastes) typically has higher levels of copper, zinc, and lead, which can accumulate in soils with repeated applications (He *et al.*, 1992). Canet *et al*. (2000) analyzed the chemical characteristics for 74 types of compost produced in Valencia, Spain (Table 2.1). Walker and O'Donnell (1991) reported concentrations of metals in compost produced by nine operational municipal solid wastes composting facilities in the United States (Table 2.2). Governo *et al.* (2003) surveyed 38 composting facilities in Georgia; Tables 2.3 and 2.4 characterize the chemical and metals content of those composts. These composts were near neutral in pH (7.0), high in organic matter content, high in nitrogen levels, and mostly low in heavy metals. The U.S. Compost Council (USCC, 1996) published the preferred characteristics of compost for various uses as noted in Table 2.5, including the particle size distribution. Table 2.6 lists the 2009 specifications for compost particle size.

Effects of Compost on Soil Properties

While several investigators (Giusquiani *et al.*, 1988; Hernando *et al.*, 1989; Shiralipour and Aziz 1992; Faucette, 2004) have documented the benefits of applying compost, limitations exist. Organic acids present in the compost may contribute to phytotoxicity and minimize vegetation growth on soil (Kirchhoff *et al*., 2002). Composts with a high carbon-to-nitrogen ratio immobilize nitrogen, which can cause nitrogen deficiency in plants.

Khaleel *et al*. (1981) summarized changes in soil physical properties caused by organic waste applications. In general, the effects of organic waste on soil physical properties largely depended on the rate of decomposition and the rate incorporation into soil organic carbon. Short-term experiments indicated greater increases in carbon, whereas long-term studies indicated smaller carbon increases. The addition of organic matter also decreased soil bulk densitydue to dilution caused by mixing lighter organic matter with the more dense mineral soil particles. Water holding capacity tended to increase with addition of organic matterwhich increased total pore space and decreased bulk density. More specifically, Agelides and Londra (2000) found that application of 70 tons per hectare of compost decreased soil bulk density, confirming the findings obtained by Khaleel *et al.* (1981) and Tester (1990). Garcia-Gil *et al.* (2004) found that the water holding capacity increased with compost addition at rates of 15, 30, and 60 tons per hectare and the stability of soil aggregates was increased by addition of compost at rates of 30 and 60 tons per hectare.

Nitrogen and metals were of particular interest in understanding soil chemical effects caused by application of compost. Alva *et al.* (1999) found inorganic nitrogen increased with addition of municipal solid waste compost but detected no change in total nitrogen, as compared with a control. These investigators also found significantly higher nitrate concentrations in for the intermediate to high compost application rates, whereas ammonia showed a significant increase at only the highest compost application rate. Mukhtar *et al.* (2008) analyzed erosion control compost based on dairy manure compostmixed with wood chips. Erosion control compost yielded 4 to 10 fold greater total Kjeldahl nitrogen, orthophosphate, total phosphorus, and total potassium mass losses under two vegetative covers. Giusquiani *et al.* (1988) showed an increase in zinc, iron, copper, and available manganese with the addition of 2.5 percent of composted municipal sewage sludge to sandy silt loam during a 12-month incubation period. Only zinc leached in toxic amounts. The USCC (1996) stated that compost may conversely cause soil binding of heavy metals by altering soil chemistry, including pH and cation exchange capacity.

General Uses of Compost

Compost has been widely used to improve soils and promote vegetation establishment. The California Integrated Waste Management Board investigated projects state-wide that had applied compost and concluded that green material compost was an excellent soil amendment for erosion control and revegetation of degraded soils (Claassen, 2000). Studies that were more recent (Faucette *et al.*, 2006; Marie *et al.*, 2006; Singer *et al.*, 2006; Gao *et al.*, 2008) confirmed that compost can improve seed survival and revegetation.

Other innovative uses of compost were summarized by USEPA (1997) as follows:

1. Erosion control: On construction sites where vegetation and topsoil have been removed and steep embankments along roads and highway, compost can be more effective than traditional hydromulch at reducing erosion and establishing turf because compost forms a thicker, more permanent growth of vegetation due to improved organic matter content, water holding capacity, and nutrient level as previously discussed.
2. Turf remediation: Turf grasses subject to recreational uses are typically subjected to extensive wear and tear, making the turf difficult to manage and highly susceptible to diseases, pests, and soil compaction. Compost when properly formulated, is teeming with nutrients and microorganisms that stimulate turf establishment and increase resistance to common turf diseased, such as snow mold, brown patch, and dollar spot. Soil compaction is another persistent landscape management problem. Incorporating composts amended with bulking agents, such as aged crumb rubber from used tires or wood chips, into compacted soils can improve root penetration and turf establishment, increase water absorption and drainage of excess water, and enhance resistance to pests and disease

(Noble and Coventry, 2005).

3. Landscaping: As a low-cost top soil alternative, compost is being used in new construction, landscape renovation, and gardening.
4. Disease control for plants and animals: Disease control with compost for plants has been attributed to four possible mechanisms:(a) stimulation of successful competition for nutrients by beneficial microorganisms, (b) antibiotic production by beneficial microorganisms, (c) stimulate predation of pathogens by beneficial microorganism, and (d) activation of disease-resistant genes in plants by composts (Scheuerell and Mahaffee, 2002). Scientists have enhanced the natural ability of compost to suppress diseases by enriching with specific disease-fighting microorganisms or other amendments (Cotxarrera *et al.*, 2002). This amended or "tailored" compost can then be applied to crops infected by known diseases. Compost controls animal disease through mortality composting. Pathogens in poultry carcasses are destroyed during composting by the high temperatures (54°C to 68°C or 130°F to 155°F) inherent in the process (Senne *et al.*, 1994).
5. Reforestation, wetlands restoration and habitat revitalization: Compost can be used to replace of the organic material in the soils striped by erosion, flooding, and logging. Many drained wetlands have been conditioned for farming with compost with high organic content to absorb up to four times the soil weight in water and can replace essential organic materials (Arnold *et al.*, 1999).
6. Bioremediation and pollution prevention: Compost bioremediation refers to the use of a biological system of microorganism in a mature, cured compost to sequester or break down contaminants in soil or irrigated contaminated water. Microorganism and stable plant enzymes break down contaminants in soils, ground and surface waters, and air. The

contaminants are usually metabolized and transformed into humus and inert byproducts, such as carbon dioxide, water, and salts but some contaminants like trinitrotoluene are fragmented into more toxic byproducts that may or may not remain bound as the compost undergoes digenesis (Jorgensen *et al.*, 2000). This "tailored" compost is specially made with components like potatoes to treat specific contaminants at specific sites.

Compost for Erosion Control

Compost has been increasingly applied to ecologically engineer solutions for several pressing problems including erosion control along roads and highways, slope stabilization, and storm water remediation to protect surface water. USEPA (1997) recommended three scenarios of applying compost for soil erosion control: (1) blankets, (2) filter berms, and (3) filter socks. A compost blanket is a complete cover with 5 to 10 cm depth of composted material that is loosely laid on soil surface in order to prevent the soil underneath from being eroded by overland flow. A compost filter berm is a dike of compost placed perpendicular to sheet flow runoff to control erosion in disturbed areas and retain eroded sediment. Compost filter berms are generally placed along the perimeter of a site, or at intervals along the slope. A compost filter sock is a type of contained filter berm, and is usually filled in a mesh tube and used in place of traditional sediment and erosion control tools such as a silt fence or straw bale barrier (Hartin and Crohn, 2007). Depending on local circumstances, compost blankets, filter berms, and filter socks may or may not be vegetated.

The slope steepness and length at a site, potential rainfall, site activity and conditions, and type and timing of the vegetation to be established are all important factors influencing the selection and use of a compost blanket, filter berm, or filter sock for erosion control. Although these methods may be, and often are, used together, compost blankets are most frequently used.

The two methods for applying compost blankets to the soil are (1) incorporation into soil usually by tilling, and (2) loosely laying compost on soil surface as mulch cover. Tilling compost into soil is intended to stabilize aggregates, improve the water holding capacity of soil, and thus encourage vegetation growth. The second method is primarily for easy and convenient application for erosion control. Considering the convenience and labor intensity of the practices, most erosion control designers and installers favor the mulch applied compost blanket. Previous studies regarding compost for erosion control were mostly focused on surface applied compost, probably because of convenience in application and limited labor requirements compared to the other two methods.

Compost also aids in the rapid establishment of vegetation and slows surface flow velocity. Studies indicate that compost not only encourage vegetation establishment, but also enhances water infiltration capacity, erosion resistance, and reduces sediment concentration in runoff (Stewart and Ettlin, 1993; Storey *et al.*, 1996; Risse and Faucette, 2001).

Alexander (2002) reported that the efficacy of compost used for erosion control applications depends on the characteristics of the compost. In general, compost that is coarse and applied at relatively high application rates is required in areas where the soil has a high erosivity index. The coarseness of the particles in the compost absorbs the energy of the rain and reduces the flow velocity. Furthermore, coarse particles are heavier and are therefore more difficult to erode than smaller particles.

Bresson *et al*. (2001) reported that municipal solid waste compost stabilized soil aggregates, delayed crust formation and seedbed slump, postponed generation of runoff, and reduced sediment concentration in the discharge. Risse *et al*. (2004) investigated the control of runoff, erosion, and nutrients obtained with a variety of composts and mulches under simulated rainfall events. The results showed that most treatments reduced total solids loss in the runoff. Manure composts increased infiltration and were effective in erosion control at a newly constructed road right-of-way (Mukhtar *et al.*, 2004) and increased the time required to initiate runoff (Ramos and Martinez-Casasnovas, 2006) under simulated rainfall conditions. Persyn *et al*. (2004) verified that compost utilized on a highway embankment could effectively reduce runoff rate and thus erosion based on their rainfall simulation study. Other studies (Harrell and Miller, 2005; Osorio and Juan, 2006) have proven that yard waste compost and urban solid waste compost could effectively prevent soil displacement and improve revegetation on roadside slopes.

Glanville *et al*. (2004) compared the concentration and total mass of nutrient and metals in runoff from compost-treated and conventionally treated highway embankments using simulated rainfall. The findings indicated the total mass of most pollutants measured in runoff from compost plots was significantly lower than from conventional treated plot. Faucette *et al*. (2005) evaluated storm water from compost and traditional erosion control practices using three simulated rainfall events and reported that compost treatments reduced the total solids loss. Findings of that study also indicated decreased total nitrogen and total phosphorus concentrations compared to traditional practices. In another study comparing the erosion control effectiveness of compost, straw with polyacrylamide, and mulch using both simulated and natural rainfall events, Faucette *et al.* (2007) reported that soil loss from plots covered by compost was significantly lower than from plots covered by straw or mulch.

The slope steepness and length at a site, potential rainfall, site activity and conditions, and type and timing of the vegetation to be established are all important considerations when deciding whether to use a compost blanket, filter berm, or filter sock for erosion control. Although these methods may be, and often are, used together to achieve effective erosion prevention (Faucette *et al.*, 2003), compost blankets are most frequently used. Recent research on compost used for erosion control is given in Table 2.7.

Guidelines and Specifications for Compost Used for Erosion Control

By 2001, 31 U.S. state departments of transportation (DOT) adopted specifications for compost as soil amendment and 11 states allowed compost use in erosion control (8 states allowed blankets and 3 allowed berms). Although there are many *ad hoc* success stories of using compost for erosion control, many states do not have design specifications and the use rates vary widely (Alexander, 2007). A national specification for using compost blankets in erosion and sediment control has been developed and approved by the American Association of State Highway and Transportation Officials (AASHTO) (Alexander, 2003). This national specification was developed primarily based on the field experience. The details of this specification are shown in Table 2.8 and Table 2.9. The USEPA (2006) endorsed this national specification and officially accepted compost blankets as a best management practice for storm water and erosion control. Many states adopted the AASHTO specifications for erosion control using compost blankets since 2001 with additional state-to-state adjustment based on a rainfall index and rainfall erosive factors. Today, compost blankets for erosion control are used extensively at a variety of sites, both on steep and flat slopes.

A warning in the specification and the USEPA guidance states, “Compost blankets should not be applied on areas where concentrated flow may occur.” However, the AASHTO specifications state that compost blankets can applied to slopes as steep as 2:1 (horizontal to vertical distance) and even 1:1 if netting or other special practices are used to stabilize the compost (Alexander, 2003; USEPA, 2006). Concentrated flow may occur as rainwater locally saturates the compost and sheet-flow concentrates due to irregularities, or concentrated flow from upstream areas runs onto the compost. Although the California specifications extend compost 3 feet beyond the top of a slope on which a blanket is applied (Hartin and Crohn, 2007), rills formed in compost are often observed even at gradual slopes. Figure 2.1 demonstrates a rill formed in a compost blanket applied at a construction site with a slope of 3.5 percent.

Estimation of Compost Erosion

Most studies have focused on the ability of compost to reduce erosion caused by rainfall impact or interill erosion. The loss of compost due to rill erosion, which may lead to failure of a blanket used for erosion control, has not been given sufficient attention. A notable exception is the work by Persyn *et al*. (2005) who investigated rill erosion on compost. They found that compost floated when concentrated flows were introduced and suggested that rill erosion of compost might be similar to the erosion observed for unanchored crop residues (Foster *et al.*, 1982). However, significant uncertainty was reported due to the small size of test plots (0.2 m as plot width) which resulted in extensive preferential flow along the plot boundaries, and movement of compost down slope in bulk rather than as individual particles. Xiao and Gomez (2009) investigated erosion resistance for three commonly used composts and the effects on slope stability. They applied simulated rainfall on a 0.91 m by 0.30 m plot inclined at a 50 percent slope. Findings of this research indicated that different composts possessing different properties such as density, particle size distribution, and organic matter content, may vary significantly in erosion resistance (Xiao and Gomez, 2009). Insightful investigation on the fundamental mechanisms and physical processes of erosion on compost is needed to develop sufficient confidence on reliable performance of compost blankets for erosion control. Development of models that can properly represent and calculate the loss of compost under certain conditions is needed.

As few studies have investigated the impacts of concentrated flow on erosion of compost, research on sediment loss caused by soil rill erosion was reviewed to investigate its applicability to solids loss from compost. An equation describing sediment transport rate as a function of bed-load flow shear stress was developed by DuBoys in 1879 (Yalin, 1977) is:

$$q_v = K'\tau(\tau - \tau_c) \quad (1)$$

where q_v is the volume transport rate of the bed-load per unit width (m^2 s^{-1}), K' is the sediment parameter (m^2 s^{-1} Pa^{-2}), τ is the flow shear stress (Pa), and τ_c is the critical shear stress (Pa). This formula was later changed to a power function by O'Brien and Rindlaub in 1934 and adopted for soil erosion research by Meyer in 1964 (Elliot *et al.*, 1989):

$$D = K(\tau - \tau_c)^b \quad (2)$$

where D is the soil detachment rate (g s^{-1} m^{-2}), K the soil erodibility (g s^{-1} m^{-2} Pa^{-1}), τ the flow shear stress (Pa), τ_c the critical shear stress (Pa), and b a coefficient, the term τ is computed by γRS, where γ is the specific weight of water (N m^{-3}), R the hydraulic radius (m), and S the hydraulic energy gradient (m m^{-1}). Previous investigators found b close to 1.0 (Van Liew and Saxton, 1983; Foster *et al.*, 1984; Elliot *et al.*, 1989; King *et al.*, 1995) . With coefficient b was 1.0, Equation (2) could be expressed as

$$D = K(\tau - \tau_c) \quad (3)$$

Equation (3) was used in the water erosion prediction project (WEPP) model (Elliot *et al.*, 1989), where D was defined as the soil detachment rate with pure water. When other than pure water is the erosive agent, rill detachment includes a feedback term ($1 - q_s/T_c$), where q_s is the sediment detachment load (kg m s^{-1}) and T_c is the flow transport capacity which is not significant for short test sections of soil. Besides Elliot *et al.*(1998), equation (3) has been utilized by King *et al.* (1995) and Persyn *et al.* (2005) to estimate the rill erodibility parameters for soil and compost, respectively. Equation (3) is used in this dissertation to estimate solids loss from compost and the erodibility and critical shear stress parameters of compost.

Buckingham Π Theorem as Dimensional Analysis

The Buckingham Π Theorem, developed by Buckingham (1915), is a key method for dimensional analysis. The Buckingham Π Theorem states that the number of dimensionless and independent groups required to express a relationship among the variables describing any phenomenon is equal to the number of quantities involved minus the number of dimensions (i.e., length, time, or mass) with which those quantities may be measured. In equation form, the Buckingham Π Theorem is

$$s = n - b$$

in which *s* is the number of dimensionless π groups, *n* is the total number of important variables involved, and *b* is the number of basic dimensions involved (Murphy, 1950). By manipulating the dimensionless Π terms, which are formed with important variables relevant to phenomenon, Buckingham Π Theorem analysis provides qualitative relation to describe a phenomenon. Combining with careful experimental investigation, a quantitative relation describing a phenomenon could be derived based Buckingham Π Theorem analysis.

Buckingham Π Theorem analysis calls for insightful investigation of the fundamental physical process of a phenomenon to select the important variables that are pertinent to the phenomenon. The general processes of conducting Buckingham Π Theorem analysis include (Murphy, 1950; Stahl, 1962; Sonin, 2004):

1. Clearly define a problem and identify the important variables pertinent to the problem;
2. Express variables in terms of their dimensions;
3. Determine the number of Π terms and select primary variables which are used to

express other variables in term of dimensions;

4. Form dimensionless Π terms and express qualitative relation among those Π terms;
5. Determine a function by combining experimental data with dimensionless Π terms.

Because the problem of solids loss from compost blankets under concentrated flow conditions have not been previously studied, the Buckingham Π Theorem analysis was selected to provide insight into the physical process of solids loss from compost blankets, and to develop a function to represent the solids loss from compost blankets under concentrated flows.

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Table 2.1 Characteristics of 74 composts from Valencia, Spain

Characteristic	Range	Mean	Std. Dev.	# of Samples
Moisture (percent)	5.4 to 45.9	26.2	11.9	70
Inert Materials (percent)	2.0 to 55.9	22.9	16.6	46
pH	6.09 to 8.25	7.15	0.49	72
Electrical conductivity (dS/m)	3.1 to 14	9.5	2.1	74
Organic Matter (percent)	22.4 to 71	53.9	10.4	74
Total nitrogen (percent)	0.6 to 2.32	1.55	0.37	72
Organic nitrogen (percent)	0.6 to 2.27	1.54	0.36	69
Carbon-to-nitrogen Ratio	9 to 36.5	21.2	4.9	72
Orthophosphate (percent)	0.4 to 2.4	1.27	0.5	70
Potassium oxide (percent)	0.27 to 1.6	0.73	0.28	70
Calcium oxide (percent)	7.7 to 27	14	5.28	70
Magnesium oxide (percent)	0.54 to 3.1	1.32	0.53	70
Sodium (percent)	0.1 to 1.5	0.76	0.26	70
Iron (mg/kg)	5000 to 25,600	11,700	5,200	33
Manganese (mg/kg)	85 to 743	262	177	33
Cadmium (mg/kg)	<0.4 to 6.23	1.66	1.58	67
Copper (mg/kg)	100 to 1790	400	270	68
Chromium (mg/kg)	16 to 944	198	240	67
Mercury (mg/kg)	<0.2 to 14.7	1.5	2.2	49
Nichel (mg/kg)	10 to 415	61	63	67
Lead (mg/kg)	110 to 771	326	188	67
Zinc (mg/kg)	340 to 2100	820	390	68

Table 2.2 Heavy metals in municipal solid wastes compost from operating facilities in the United States.

	Agrisoil	Fairgrow	Fillmore	St. Cloud	Sumter	Sludge
Mean (mg/kg dry weight)						
Cadmium	4.1	3.4	2.9	2.2	5.0	6.9
Chromium	20.5	223	12.8	33.5	--	119
Cooper	246	285	101.5	180	250	741
Mercury	2.4	4.0	1.2	1.8	--	5.2
Nickel	34	77	15.1	28	27	43
Lead	124	496	82.4	185	290	134
Zinc	607	1008	329	390	580	1202
Range (mg/kg dry weight)						
Cadmium	ND-8.3	2.3-7.0	1.4-4.4	1.3-3.03	1-8.2	
Chromium	2.1-43.4	159-828	9.3-16.2	23-44	--	
Cooper	5.1-1053	190-972	101-102	110-250	240-260	
Mercury	1.5-3.2	0.6-5.9	0.1-1.4	0.7-1.2	--	
Nickel	3.2-99	139-709	12.4-17.8	20-36	14-49	
Lead	<.6-287	348-1250	--	140-230	280-300	
Zinc	4.1-4886	596-1370	328-330	310-470	560-600	

Table 2.3 Summary of the analyses of compost samples from the 2002 Georgia survey of 38 composting facilities.

Facility Type		Moisture (percent)	Volatile Solids (percent)	pH (S.U.)	Soluble Salts (mmhos)	Carbon-to-Nitrogen Ratio	Total Kjeldahl Nitrogen (percent)	Phosphorus (percent)	Potassium (percent)
Total	Avg	34	26	6.6	4.4	23	0.9	0.31	0.42
	St.D	12	12	1.1	5.4	7.5	0.7	0.41	0.64
	Min	7	0	5.0	0.1	8	0.2	0.01	0.01
	Max	68	51	8.6	25.2	147	3.6	1.89	3.45
	n	34	24	34	33	34	34	34	34
Institution	Avg	31	29	6.4	2.9	19	1.0	0.12	0.23
	St.D	15	30	1.0	0.4	20	0.5	0.02	0.05
	Min	7	0	5.0	0.1	8	0.4	0.03	0.08
	Max	46	51	7.8	7.5	36	3.6	0.25	0.52
	n	10	10	10	10	10	10	10	10
Private	Avg	34	23	6.9	5.8	27	0.9	0.40	0.55
	St.D	13	9	1.1	7.2	33	0.8	0.54	0.82
	Min	15	16	4.9	0.7	9	0.2	0.01	0.02
	Max	68	40	8.6	25.2	147	3.4	1.89	3.45
	n	17	8	17	16	17	17	17	17
Local Government	Avg	36	25	6.4	3.5	22	0.8	0.31	0.36
	St.D	8	10	1.4	3.3	11	0.3	0.31	0.56
	Min	25	18	5.0	0.1	9	0.6	0.07	0.06
	Max	45	45	8.4	9.9	42	1.2	0.66	1.63
	n	7	6	7	7	7	7	7	7

Avg - average; St.D - standard deviation; Min - minimum; Max - maximum; n - number of samples. All analyses on an as is basis.

Table 2.4 Summary of the metal analyses of compost samples collected from the 2002 Georgia survey of 38 composting facilities.

Facility		Aluminum (mg/L	Cadmium (mg/L)	Chromium (ppm)	Copper (mg/L)	Magnesium (mg/L)	Molybdenum (mg/L)	Nickel (mg/L)	Lead (mg/L)	Zinc (mg/L)
Part 503 Limits[1]			39	1,200	1,500		18[2]	420	300	2,800
Total	Avg	9,688	2.2	14.9	68.1	1,670	1.1	11.7	11.2	292
	St.D	7,041	2.0	22.9	153	1,553	1.0	22	21.6	1,079
	Min	1,219	0.2	0.5	0.5	120	0.5	1.0	2.5	4.3
	Max	25,490	7.9	137	677	6,869	3.9	123	118	6,365
	n	34	34	34	34	34	34	34	34	34
Institution	Avg	10,708	2.6	8.9	9.8	845	0.6	7.1	2.5	36
	St.D	1,110	3.3	10.7	13	144	0	16.3	0	4.7
	Min	2,130	0.5	1.8	0.5	280	0.5	1.0	2.5	11.3
	Max	25,390	7.9	25.3	29.2	1,880	1.1	31.6	2.5	53.8
	n	10	10	10	10	10	10	10	10	10
Private	Avg	8,539	1.6	10.8	109	2,239	1.4	8.3	13	485
	St.D	6,406	1.4	7	209	1,956	1.2	11	12.8	1,520
	Min	1,219	0.2	0.5	0.5	120	0.5	1.0	2.5	4.3
	Max	25,490	5.2	23.8	677	6,869	3.9	42.6	40.2	6,365
	n	17	17	17	17	17	17	17	17	17
Local Government	Avg	11,020	2.9	33.6	51.7	1,467	1.2	26.8	19.1	187
	St.D	8,012	1.8	46.6	41.1	774.5	1.0	43.2	43.8	133
	Min	4,577	0.8	4.2	6.9	495	0.5	2.9	2.5	50.2
	Max	24,770	4.9	136	106	2,945	2.7	123	118	372
	n	7	7	7	7	7	7	7	7	7

Avg - average; St.D - standard deviation; Min - minimum; Max - maximum; n - number of samples. All analyses on an as is basis.

[1]USEPA 40 CFR Part 503, Table 3 Pollutant Limits.

[2]No longer part of the 503 regulations.

Table 2.5 US Composting Council (1996) compost use guidelines.

Compost use or market	Application	pH	Particle size	Soluble salt content	Stability
Turf	Soil amendment	5.5-8.0	<25 mm (<1 in.)	<4 dS/m	Stable
Vegetable crop	Soil amendment	5.0-8.0	<25 mm (<1 in.)	<6 dS/m	Stable
Silviculture[2]	Soil amendment	5.5-8.0	Must report	Must report	Moderate
Marginal soils	Soil amendment	5.5-8.0	Must report	Must report	Moderate
Planting beds	Soil amendment	5.5-8.0	<25 mm (<1 in.)	<2.5 dS m^{-1}	Stable
Nursery beds	Soil amendment	5.5-8.0	<25 mm (<1 in.)	<3 dS m^{-1}	Stable
Field nursery	Soil amendment	5.5-8.0	<25 mm (<1 in.)	<3 dS m^{-1}	Stable
Horticultural substrate	Soil media component	5.5-8.0	<13 mm (<1/2 in.)	<3 dS m^{-1}	High
Blended topsoil	Soil media component	5.5-8.0	Must report	<6 dS m^{-1}	Moderate
Planting backfill	Soil media component	5.5-8.0	<25 mm (<1 in.)	<3 dS m^{-1}	Stable
Sod production	Soil media	5.0-8.0	<10 mm (<3/8 in.)	<3 dS m^{-1}	Stable
Landscape mulch	Surface application	5.5-8.0	Must report	Must report	Moderate
Erosion control[3]	Surface application	5.5-8.0	Must report	Must report	Must report

Note: All compost uses must report nutrient content, water holding capacity, bulk density, organic matter content, plant growth screening test, moisture contents between 35 percent and 55 percent, and not exceed USEPA Part 503 Table Pollutant Concentrations[1] for heavy metals.

[1] USEPA Part 503 Table 3 Pollutant Concentration Limits (mg kg^{-1}). Arsenic = 41; cadmium = 39, copper = 1500, lead = 300; mercury = 17, nickel = 420, selenium = 100, zinc = 2800.

[2] Does not have to meet USEPA Part 503 Exceptional Quality Concentration Limits for trace elements and heavy metals.

[3] Plant growth screening test not required; moisture content must be reported.

Table 2.6 Current specifications of particle size distribution for compost used for erosion control.

Agency	**Percent passing 50 mm**	**Percent passing 25 mm**	**Percent passing 18 mm**	**Percent passing 6 mm**
TX DOT	95 %	65 %	65 % (16 mm)	50% (9.5 mm)
AASHTO	100 % (75 mm)	90 % to 100 %	65 % to 100 %	0 to 75 %
USEPA	100 % (75 mm)	90 % to 100 %	65 % to 100 %	0 to 75 %
Indiana Department of Natural Resources	100 %	99 %	90 %	0 to 90 %
CONEG	100 %	100 %	100 %	70 % (13 mm), 50 % (2 mm)

Table 2.7 Investigation of compost for erosion control

Treatment	**Erosive agent**	**Slope**	**Field or laboratory, plot size**	**References**
Dairy manure compost, compost manufactured topsoil, general use compost, erosion control compost	Natural rainfall	8.50 %	Field	(Hansen *et al.*, 2009)
Wood chip, yard waste compost blanket, Compost : woodchip=2:1 Compost : woodchip=1:2	Natural rainfall: 48 in, simulated rainfall: 100 mm h^{-1} (4 in h^{-1})	10 %	Field, 4.8 m by 1 m	(Faucette *et al.*, 2006; Faucette *et al.*, 2007)
Biosolid compost, yard waste compost, bio-industrial waste compost	Simulated rainfall: 100 mm h^{-1}	33.30 %	Field: 1.2 m by 1.5 m	(Glanville *et al.*, 2004; Persyn *et al.*, 2004; Persyn *et al.*, 2005)
Compost manufactured topsoil, daily manure compost, erosion control blanket, manure compost mixed with woodchip.	Simulated rainfall: 88.9 mm h^{-1}	33.30 %	Field: 2 m by 1 m	(Mukhtar *et al.*, 2004)
One compost with dosages: 0, 40, 60, 80 mg hg^{-1}	--	66.6 %, 50 %	Field: 5 m by 4 m	(Osorio and Juan, 2006)
Sewage sludge compost	Natural rainfall: 60 mm	53 %	Field: 6 m by 5 m	(Gao *et al.*, 2008)
Compost, mulch	Natural rainfall	10 %	Field: 22.1 m by 4 m	(Edwards *et al.*, 2000)
Erosion control compost, inorganic fertilizer	Simulated rainfall: 88.9 mm h^{-1}	33.30 %	Laboratory: 1.8 m by 0.9 m	(Mukhtar. *et al.*, 2008)
Green compost, manure compost, mixed biosolid and green compost	Simulated rainfall: 79 mm h^{-1} (3.1 in h^{-1})	50 %	Laboratory: 0.91 m by 0.3 m	(Xiao and Gomez, 2009)

Table 2.8 National specifications for compost blankets used for erosion control (Alexander, 2003)

Parameters[1,4]	Reported as (units of measure)	Surface Mulch to be Vegetated	Surface Mulch to be left Un-vegetated
pH[2]	pH units	5.0 - 8.5	N/A
Soluble Salt Concentration[2] (electrical conductivity)	dS/m (mmhos/cm)	Maximum 5	Maximum 5
Moisture Content	%, wet weight basis	30 – 60	30 – 60
Organic Matter Content	%, dry weight basis	25 – 65	25-100
Particle Size	% passing a selected mesh size, dry weight basis	• 3" (75 mm), 100% passing • 1" (25mm), 90% to 100% passing • 3/4" (19mm), 65% to 100%passing • 1/4" (6.4 mm), 0% to 75% passing • Maximum particle length of 6" (152mm)	• 3" (75 mm), 100% passing • 1" (25mm), 90% to 100% passing • 3/4" (19mm), 65% to 100%passing • 1/4" (6.4 mm), 0% to 75% passing • Maximum particle length of 6" (152mm)
Stability[3] Carbon Dioxide Evolution Rate	mg CO_2-C per g OM per day	< 8	N/A
Physical Contaminants (man-made inerts)	%, dry weight basis	< 1	< 1

[1] Recommended test methodologies are provided in Test Methods for the Examination of Composting and Compost (TMECC, The US Composting Council)

[2] Each specific plant species requires a specific pH range. Each plant also has a salinity tolerance rating, and maximum tolerable quantities are known. When specifying the establishment of a plant or turf species, it is important to understand their pH and soluble salt requirements, and how they relate to the compost in use.

[3] Stability/Maturity rating is an area of compost science that is still evolving, and as such, other various test methods could be considered. Also, never base compost quality conclusions on the result of a single stability/maturity test.

[4] Landscape architects and project (field) engineers may modify the allowable compost specification ranges based on specific field conditions and plant requirements.

Table 2. 9 National specification for compost application rates(Alexander, 2003)

Annual Rainfall/Flow Rate	Total Precipitation & Rainfall Erosivity Index	Application Rate For Vegetated* Compost Surface Mulch	Application Rate For Unvegetated Compost Surface Mulch
Low	1-25”, 20-90	½ - ¾ ” (12.5 mm - 19 mm)	1” – 1 ½” (25 mm – 37.5mm)
Average	26-50”, 91-200	¾ - 1” (19 mm - 25 mm)	1 ½” – 2” (37 mm – 50 mm)
High	51” and above, 201 and above	1-2” (25 mm - 50 mm)	2-4” (50mm – 100mm)

Figure 2.1 A picture showing a rill forms in compost applied on a construction site with slope of 3.5 percent. (Photo by Xianben Zhu)

CHAPTER 3

LABORATORY RILL EROSION OF COMPOST BY CONCENTRATED FLOW[1]

[1] Zhu, X., L.M. Risse, S. C. McCutcheon, E. W. Tollner, T. C. Rasmussen, and L.T. West. Accepted by *Transactions of the ASABE* November 18, 2009

Abstract

Yard waste compost and a bare Cecil soil control responded to concentrated laboratory runoff similarly in rill formation and the shear stress model was useful in estimating sediment yields from both of these land covers. Critical shear stress for yard waste compost and Cecil soil were not significantly different, however, the erodibility of the soil was higher resulting in increased solids loss on soil contrl. Micro-dams, the main mechanism for limiting soil erosion for the compost, often occurred in the rills causing the concentrated flow to infiltrate and fan out through the erosion control compost. This investigation could not accurately parameterize the shear stress model for erosion control compost due to micro-dams forming in the rills that redirected and spread the concentrated flow out, resulting in non-concentrated flow and an inability to measure flow velocities or rill width needed to calculate shear stress.

Introduction

Compost improves the physical, biological, and chemical properties of soil by increasing water holding capacity, total pore space, aggregate stability, temperature insulation, pH, electrical conductivity, cation exchange capacity, and nutrient availability (Zhu and Wong, 1987; Hernando *et al.*, 1989; Shiralipour *et al.*, 1992). By changing the soil fertility, compost contributes to the establishment of the vegetation on construction sites, highway embankments, and other disturbed lands. In addition to aiding vegetation establishment, compost enhances water infiltration and reduces erosion and sedimentation from runoff (Stewart and Ettlin, 1993; Storey *et al.*, 1996; Risse and Faucette, 2001). The USEPA (1997) issued guidance for using compost to remediate turf grasses, enhance landscaping, and control plant and animal diseases, in addition to using it for erosion control.

The use of compost for soil erosion control in particular has been widely investigated. The Integrated Waste Management Board in California investigated applications of compost state-wide and concluded that compost derived from plant or green material was an excellent soil amendment for erosion control and revegetation of degraded soils (Claassen, 2000). Bresson *et al*. (2001) reported that municipal solid waste compost stabilizes soil aggregates, delays crust formation and seedbed slump, postpones generation of runoff, and reduced sediment concentrations in the runoff. Risse *et al*., (2004) found that a variety of composts and mulches were effective in reducing runoff, erosion, and total solids and nutrient losses during simulated rainfall events. Manure composts subject to simulated rainfalls (1) increased infiltration and were effective in erosion control at a newly constructed road right-of-way (Mukhtar *et al.*, 2004) and (2) delayed initiation of runoff (Ramos and Martinez-Casasnovas, 2006). Rainfall simulations by Persyn *et al*., (2004) verified that compost on a highway embankment effectively reduced runoff and erosion. (Harrell and Miller, 2005; Osorio and Juan, 2006) established that yard waste compost and urban solid waste compost effectively prevented soil erosion and improved revegetation on embankments.

Comparing the concentration and total mass of nutrients and metals in runoff generated by simulated rainfall from highway embankments, Glanville *et al*. (2004) found that the total mass of most pollutants from compost treated plots were significantly lower than conventional stabilization techniques. Faucette *et al*. (2005) evaluated three runoff events over a year generated by simulated rainfall and showed that compost reduced the total solids, nitrogen, and phosphorus losses compared to hydroseed and silt fence controls. Later comparing compost, straw with polyacrylamide, and mulch subjected to both simulated and natural rainfall, Faucette *et al*., (2007) reported that compost permitted less soil loss than straw or mulch.

As a best management practice, practitioners extensively apply compost on flat areas and steep slopes. For national uniformity and reliability in practice, the American Association of State Highway and Transportation Officials (Alexander, 2003) developed standards for the use of compost in erosion control. The USEPA (1997) endorsed compost for erosion control but cautioned against using compost on areas where concentrated flow is likely.

Because most of studies have focused on interrill or sheet erosion during rainfall, little guidance is available for design of compost applications subjected to concentrated flow. Persyn *et al*., (2005) investigated rill erosion of compost and suggested that the cause might be similar to erosion of unanchored crop residues (Foster *et al.*, 1982). He attempted to apply the shear stress model to estimate solids loss due to concentrated flow and found that the model did not accurately predict solids loss. However, significant uncertainty occurred due to floatation of compost particles, small test plots (0.2 m as plot width) that allowed notable preferential flow along the plot boundaries, and movement of compost down slope in *en masse* rather than as individual particles. Thus, Persyn *et al*. (2005) suggested that erosion in rills might be different for soils versus compost, but that indication was not followed up with additional studies.

This study went beyond Persyn *et al*., (2005) to investigate the null hypothesis that the rill erosion of compost is similar to the erosion of soil. The specific objective was to determine if the shear stress equation based on the critical shear stress and the rill erodibility describe rill erosion from compost. As in Persyn *et al*., (2005), other types of erosion—sheet, gully, and streambed or bank erosion—were not included. The soil rill erosion investigated in this study occurs when water moving over the soil surface flows along preferential pathways forming an easily recognizable channel(Rose *et al.*, 1983). Hydraulic shear stress (N m^{-2}) is a function of soil rill erosion which is governed by shear stress model (Foster *et al.*, 1984; Elliot *et al.*, 1989; Nearing and Parker, 1994; King *et al.*, 1995):

$$D_r = K_r(\tau - \tau_c) \qquad (1)$$

where

D_r = rill erosion rate (g s^{-1} m^{-2}),

K_r = rill erodibility factor (s $m^{-1} 10^{-3}$),

τ_c = critical shear stress (Pa).

Both soil-specific constants rill erodibility factor, K_r , and critical shear stress τ_c, can be determined from the shear stress equation. Erodibility is a soil property quantified in terms of sediment loss, which this study hypothesized, is applicable also to solids loss from compost. In a rectangular channel, the hydraulic shear stress (τ) is independently calculated as:

$$\tau = \gamma R S \qquad (2)$$

where,

γ = the specific weight of the flowing fluid (N m^{-3}),

R = hydraulic radius (m),

S = slope of the channel (m m^{-1}).

Materials and Methods

Fluid Mechanics Laboratory Flume

This study investigated rill erosion in an aluminum hydraulic flume 4.0 meters long, 1.0 meter wide, and 0.7 meters high (Figure 3.1) divided into two sections by a piece of sheet metal forming a V notch weir near the entrance. This upstream section served as a 1-m-long reservoir, leaving a 3-m-long test section. Compost or soil was placed on the flume bed to a depth of 5 cm and a 2.5-cm-deep and 25-cm-wide rectangular channel was formed along the centerline of the test section prior to each test. The rectangular channel maintained the concentrated flow and restricted rill formation to the middle of the test area. The flume was tilted to achieve the desired slope for different tests.

Water pumped into the upstream section at a rate controlled by a valve and measured by rotameter flowed through the V notch weir and formed concentrated flows within the test section. A 0.8-m long by 0.2-m wide by 0.2-m high aluminum structure with a reversed vaulted face dissipated the energy of the weir overflow and directed the water to the inlet of the rectangular channel pre-formed in the test materials.

Compost and Soil

The University of Georgia Bioconversion research and education center provided yard waste compost made from campus landscape trimmings and woody debris. A commercial facility with the Seal of Testing Assurance as designated by the United States Composting Council (USCC, 1997) donated the erosion control compost, a 1:1 blend of mulch and yard waste compost with a maximum particle size of 5 cm. The Cecil soil (Figure 3.1) was collected from the USDA-ARS J.Phil Campbell Sr. Natural Resource Conservation Center located at Watkinsville, Georgia, the same location where the Water Erosion Protection Project (WEPP) (Elliot *et al.*, 1989) measured rill erodibility parameters in the field for the Cecil soil series. The 10 cm top layer was removed at the site and the Cecil soil sample was collected from the B horizon. Basic physical properties and organic matter content of the two composts and the soil (Figure 3.2 and Table 3.1) were determined by the Test Methods for Examination of Compost and Composting (USCC, 1997) after drying at 75℃ for 1.5 h.

Libratory Flume Observation

Water was initially ponded in the flume by leveling it and raising the outlet barrier for 10 min to pre-wet each compost or soil tested. Consistency between the inflow and discharge rates confirmed effective saturation of the composts or soil during testing. For each of the four slopes to which the flume was set (1 percent, 3 percent, 5 percent, and 7 percent), four sequential inflow rates were released onto each slope. The smallest flow rate was determined based on previous trials for which rill erosion occurred. The subsequent flow rates were increased between 5 L min^{-1} and 10 L min^{-1} for soil, between 8 L min^{-1} and 15 L min^{-1} for yard waste compost, and between 8 L min^{-1} and 20 L min^{-1} for erosion control compost depending on the flume slope. The duration for each inflow rate was 30 min. Discharge was measured at 3-min intervals (during the remaining 27 min) by recording the time required to fill a two-liter bucket. 10 sediment samples were collected using 500 ml bottles after the initial 3 min of constant inflow. Constant flow was assured by confirming no significant change in discharge rate for two sequential discharges in 3 min.

The experimental protocol required weighing sediment samples and oven drying at 105℃ until a constant weight occurred. The sum of dried sediment weight in the ten samples divided by the total volume of the collected discharge samples produced the mean solids concentration of the discharge, which was used to calculate the total amount of solids loss from a run by multiplying by the total amount of discharge in the run. The total amount of solids loss divided by the test duration and the area of erosion, which was assumed to be the average width of the rill multiplied by the length of the channel, was the erosion rate.

Surface flow velocity was measured by timing the advancement of the leading edge of a dye within a one-meter test section. The test section for velocity was selected at the central part along the channel, for the purpose of avoiding severe fluctuation and turbulence at both the beginning and ending parts of the channel. Average velocity was calculated by multiplying measured leading edge velocity by a factor of 0.7 (Elliot *et al.*, 1989; Persyn *et al.*, 2005). The width of rills was measured at 10 test points which were evenly assigned along the channel. Depth of the rill was measured using a vertical depth meter at the 10 test points (Figure 1). The ten measurements of rill depth were conducted at each test point by moving the vertical depth meter across the pre-created channel in 2.5 cm intervals. The measurements of discharge, velocity, and rill width were conducted in 3-min intervals; the depth measurements were made after each run was completed.

Shear stress values were calculated using equation (2), where specific weight of water was $\gamma = 9800$ N m^{-3}, the average hydraulic gradient was equal to the flume slope, and the hydraulic radius R (m) was calculated for a rectangular cross-section of the rill

$$R = \frac{A}{P} \qquad (3)$$

where

P = wetted perimeter (m) = width + 2 $\times$ depth.

A = cross-sectional area of flow (m^2) = width $\times$ depth was calculated using the continuity equation:

$$A = \frac{Q}{V} \qquad (4)$$

where,

Q = flow discharge (m^3 s^{-1}),

V = average flow velocity (m s^{-1}).

Statistical Analysis

SAS version 9.1 (SAS, 2002) was used for statistical analysis. In order to easily derive and compare the critical shear stress values between Cecil soil and yard waste compost, equation (1) was rewritten as equation (5) in which intercept is critical shear stress value.

$$\tau = \frac{D_r}{K_r} + \tau_c \qquad (5)$$

Equation (2) was used to fit the erosion data of both Cecil soil and yard waste compost for each separate slope level, as well as by lumping all the data from the four different slopes together. Dummy variables were introduced to estimate the combined coefficients of both Cecil soil and compost data, and equations representing rill erosion on Cecil soil and yard waste compost were determined. A dummy variable takes values of 1 and 0 in regression analysis to indicate different cases (Rasmussen, 2009). A Dummy variable representing the change in slope from the base case (Cecil soil) to the alternative (yard waste compost) was applied. Let $m = \frac{1}{K_r}$, then equation (5) could be rewritten as

$$\tau = m\, D_r + \tau_c \qquad (6)$$

with dummy variable for m, equation (6) becomes

$$\tau = (m + \Delta m\, d) D_r + \tau_c \qquad (7)$$

where Δm represents the change in slope from Cecil soil to yard waste compost. Equation (4) combined the relationship between shear stress and erosion rate for both Cecil soil and yard waste compost, d=0 for Cecil soil, and d=1 for yard waste compost. Multiple regressions were conducted, using both Cecil soil and yard waste compost dada, to fit equation (7). Student *t* tests were performed to determine any significant differences between treatments at α = 0.05.

Results and discussion

Observations

The rills formed quickly on both the Cecil soil and yard waste compost as concentrated flow ran on those materials; however, the evolution processes of the rills on these two materials were different. On the Cecil soil plot, bed scour within the rill started from the downstream end and advanced up the slope, while on yard waste compost, the bed scour within the rill began at the top of the pre-formed channel (Figure 3.3). While scouring occurred on both the channel bed and side walls in Cecil soil plots, which resulted in relatively wide of rills; water consistently scoured downwardly in yard waste compost. Sidewall scouring seldom occurred in the channel of yard waste compost, resulting in relatively small and consistent rills in yard waste compost. This discrepancy of responding to concentrated flows between Cecil soil and yard waste compost was primarily due to the greater pore space in yard waste compost compared to Cecil soil. The greater pore space allowed more water to penetrate through the side walls of yard waste compost channels, resulting in reduced shear stress acting on the rill channel.

The erosion control compost used in this study behaved in a different way from yard waste compost and Cecil soil. Solids loss only occurred when inflow rate was increased and quickly stabilized with little solids movement. Some light-weight particles which could not withstand the suddenly increased stress were dragged, lifted, and transported to the flume outlet by the flow. After this first flush, little erosion was detected during the period of steady flow conditions. Rather than concentrating and scouring a rill on the pre-created channel as occurred on the soil and yard waste compost, the water on erosion control compost easily infiltrated into the compost and flowed through the blanket matrix. With the coarsest particles among these three materials used in this study, erosion control compost has the largest pore space and greatest likelihood of allowing water to flow through and underneath its matrix. These properties of erosion control compost substantially reduced the amount of water flowing on the surface and thus prevented or delayed rill development on the surface.

Other than particle floatation and bulk movement of the materials down the slope as described by Persyn *et al*. (2005), the formation of "micro-dams" on erosion control compost was the key phenomenon under concentrated flow conditions, which confirms the observation made by Zhu and Risse (2009) in their field study of compost for erosion control. As inflow rate or slope steepness increased, erosion was initiated on erosion control compost as those particles at upstream part were entrained in the flow and started to roll down along the slope. These entrained particles were deposited on the way down the slope as they exceeded the transportation capacity of the flow. The deposited particles interlocked together and were able to trap more particles from upstream and accumulated quickly to form a micro-dam. The particle trapping mechanism of the micro-dams is similar to the process of sedimentation in grass filter described by Tollner *et al*. (1976). By ponding water upstream, the micro-dam retarded the flow velocity, encouraged water to flow through the channel wall and disperse on the entire compost surface and subsurface (Figure 3.4). Through this process, micro-dams promoted the shift of concentrated flow to subsurface flow in the erosion control compost. Since the amount of surface flow was significantly reduced, the shear stress acting on the channel became very small and was very difficult to calculate based on the amount of inflow. Without appropriate estimation of the shear stress values, it was impossible to apply the shear stress model to estimate the critical shear stress and erodibility values for erosion control compost.

Applications of Shear Stress Model on Cecil Soil and Yard Waste Compost

The results of fitting the lumped data to the shear stress equation to both Cecil soil and yard waste compost are shown in Table 3.2, Table 3.3, and Figure 3.5. Results indicated no statistically significant difference in critical shear stress between Cecil soil and yard waste compost. Results of regression using the introduced dummy variable to represent the change of erodiblity from Cecil soil to the yard waste compost are shown in Table 3.4, in which all the coefficients were significant. The critical shear stress for both Cecil soil and yard waste compost was 2.59Pa, the shear stress coefficient was 0.05 for the Cecil soil and 0.05+0.18=0.23 for yard waste compost. Thus, the erodibility value was 1/0.05=20.00 for Cecil soil and 1/0.23=5.42 for yard waste compost. The shear stress model for the Cecil soil and yard waste compost could be written as $D_r = 20.0 \times (\tau - 2.59)$ for Cecil soil and $D_r = 5.42 \times (\tau - 2.59)$ for yard waste compost.

Table 3.5 showed the comparison of the estimated erodibility and critical shear stress parameters for Cecil soil derived from this study and those values determined by the WEPP team when erosion experiments were conducted at the site from which the Cecil soil used in this study was collected. Even though the resulting critical shear stress and erodibility parameters between this study and the field study in 1988 do not perfectly match, those values were rationally close and provided reasonable confidence that this process of laboratory study to estimate the applicability of shear stress model was suitable. The discrepancy between the critical shear stress and erodibility values for the laboratory study and the field study in 1988 might be due to (1) different experimental processes, (2) change of properties of the soil in the site may occur due to effect of erosion and climate change during the last eighteen years, (3) changes in the soil bulk density between those in the field and a reconstituted soil in the laboratory flume, and (4) uncertainty introduced by method of data collection which transferred to the results of regression analysis. It should also be noted that all of the data collected for the WEPP study were collected at a single slope. Since the results of this analysis suggest that the values for rill erodibility and critical shear were different on various slopes, further work is needed to determine if collection of this data at a single slope condition is a valid method of determining these parameters.

The shear stress model was applied using calculated shear stress values and erosion rates from various slope levels on Cecil soil and yard waste compost, respectively. The model was applied using the three replications for four inflow rates under each slope level. The results are shown on Figures 3.6 and 3.7. The correlation coefficients and P-values of shear stress model fits for Cecil soil and yard waste compost were summarized on Table 3.6. Results showed that the rill erosion on Cecil soil for individual slopes better conformed to the shear stress model than the rill erosion on yard waste compost blanket under our experimental conditions. The regression fit of shear stress model under 1 percent slope was relatively weak for Cecil soil may be due to the fact that shear stress value was not significantly increased with added inflow, which resulted from greater portion of water weight acts downwardly and allows greater amount of water infiltrate into the soil matrix on the relatively flat surface, compared to the situations of steeper slopes.

Comparisons of applications of shear stress model under each slope level for Cecil soil and yard waste compost are shown on Figure 3.8. The regression lines derived from yard waste compost had lower slopes than the regression lines derived from Cecil soil under slope levels of 1 percent, 3 percent, and 5 percent, representing less likelihood of erosion from yard waste compost than Cecil soil under those slope levels. The fact that the slope of regression line derived from yard waste compost exceeded the slope of regression line derived from Cecil soil under slope level of 7 percent might be indication of decreased performance of yard waste compost with increased slope level. While the designed experiment of this project limited the slope level to 7 percent, further experiments using slope levels greater than 7 percent should be conducted to verify the specific constraint of slope condition to the performance of yard waste compost on erosion control.

Shear stress, erosion rate, rill erodibility, critical shear stress, and coefficient of correlation (r^2) values for each replication are summarized at Table 3.7. Only replications having a positive slope and x-intercept (no bolded) were used to estimate rill erodibility and critical shear values for statistical comparisons. In most of the cases, the shear stress model fit for Cecil soil and yard waste compost had a positive slope (rill erodibility) and x-intercept value (critical shear stress). However, some replications were opposite to the expected trend on both Cecil soil and yard waste compost, meaning that the slope of regression line was negative and that the detachment rate decreased with increased hydraulic shear stress. This phenomenon occurred one time on 3 percent, 5 percent and 7 percent slope level, respectively. This might be due to the fact that the flume bed was exposed in some cases before the run was completed. Under these conditions the calculated shear stress was not actually acting upon the compost materials vertically, resulting in overestimation of shear stress value for those runs. Similar results of negative critical shear stress and erodibility values have been reported to occur occasionally in the field testing of the WEPP study as well (Elliot *et al*, 1989).

The average erosion rate of Cecil soil was significantly higher than the erosion rate of the yard waste compost under the same level of the shear stress, based on the overall mean values derived from the 4 various slope levels. This may be due to the higher pore space on yard waste compost matrix compared to soil material, which allowed part of the water to flow into the compost matrix, rather than flowing on the surface, resulting in reduced shear force acting on the compost surface. Furthermore, unlike in the soil channel where scour holes occasionally occurred, which accelerates local turbulence; a scour hole was rarely observed in yard waste compost channels, resulting in relatively smooth flow through the entire yard waste compost channel.

The mean values of critical shear stress and rill erodibility parameters which were derived from shear stress model suggested no significant difference between Cecil soil and yard waste compost. However, there is a clear trend that the critical shear stress values were higher and the rill erodibility values were lower, even though is not significant, on yard waste compost than on Cecil soil, demonstrating the effectiveness of yard waste compost on rill erosion reduction.

The generally higher erodibility values on Cecil soil than on yard waste compost, except on 7 percent slope, indicated that yard waste compost had higher concentrated flow resistance compared to Cecil soil. It is also noted that the critical shear stress values and erodibility parameters for both Cecil soil and yard waste compost changed with various slope steepness (Figure 3.8). This was because those values were derived from the shear stress model, which showed different performances on various slope levels. It may suggest that critical shear stress and erodibility parameters are not merely related to the properties of materials; the slope conditions should be incorporated when shear stress model is applied to predict rill erosion on slope areas.

Uncertainty Analysis

Source of data scatter from this study included:

1. Cases of the flume bed being exposed while concentrated flow was still running;
2. Compost blankets and Cecil soil were not reestablished between consequent inflows in a run; instead, increased inflow was introduced on the rill generated by the prior flow, which resulted in relatively great variation of the solids loss under increased inflow or calculated shear stress.
3. Deposition along the rills was ignored when erosion rates were calculated, assuming all the detached solids are delivered to the flume outlet

4. Using the area of rill surface, did not include the area of side walls to calculate the erosion rate.

Improvement must be made on the follow-up study to reduce the abovementioned sources of uncertainty.

Conclusions

Observations and statistical analysis of this project suggest that yard waste compost responded to concentrated flow in a similar way to Cecil soil. However, the mechanisms of formation and detachment of a rill differed between compost and soil, and between different types of compost materials. This is primary due to the differences in particle sizes and pore space of those materials. The rilling process on soil was based on bed scour from downstream to upstream, while rills on yard waste compost developed by continuous scour from upstream to downstream. The unique mechanism of erosion prevention on erosion control compost was based on the formation of micro-dams, which was due to deposition and accumulation of entrained particles on flowing water. The stableness of these micro-dams relied upon the coarse particles and great pore space of erosion control compost which encourages water to flow through the matrix. The formation of micro-dams on erosion control compost did not allow us to determine shear stress as the bulk of the flow ran through the compost matrix as opposed to in the rill.

There was positive slope and positive x-intercept for the linear relationship between erosion rate and shear stress on most of the single replications, supporting the application of shear stress model on Cecil soil and yard waste compost. Without statistical differences critical shear stress applied on Cecil soil and yard waste compost, the average detachment rate was greater on Cecil soil than on yard waste compost.

The shear stress model seemed applicable to the measured data of each slope level for both yard waste compost and Cecil soil. The lower erodibility values on yard waste compost compared to Cecil soil (except on 7 percent slope) suggested the effectiveness of yard waste compost on reducing soil erosion. The erosion data from individual slopes for Cecil soil conformed to the shear stress model better than the erosion for yard waste compost. No significant difference in critical shear stress and erodibility parameters between Cecil soil and yard waste compost were found. However, there was a clear trend that yard waste compost lower erodibility than the Cecil soil.

The bulk density of tested materials in this study ranged from 170 kg m^{-3} for erosion control compost to 1240 kg m^{-3} for Cecil soil. With added pore space in the compost matrix, infiltration and diffusion of water into compost matrix are considerable. Given the fact that a great amount of water flowed through the compost matrix, the shear stress value on the compost surface was reduced, and thus the resistance of compost to concentrated flow increased. While the shear stress model used in WEPP was likely valid for yard waste compost, we were unable to estimate shear stress for erosion control compost and could not apply the shear stress model. More appropriate models or guidelines should be developed to better understand the use of these compost under concentrated flow conditions.

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Table 3.1 Bulk density, median particle size, and water holding capacity for the materials used in this study.

Material	Bulk density, kg m^{-3}	Water holding capacity, g g^{-1}	Median particle size (D_{50}), mm
Test methods	TMECC *07.01-B*	TMECC *07.01-B*	TMECC *06.02-B*
Cecil soil	1240	0.10	0.053
Yard waste compost	440	0.61	1.65
Erosion control compost	170	0.42	2.19

Note: All materials were dried at 75℃ for 1.5 h before testing

Table 3.2 Overall fits of shear stress equation to Cecil soil, using data lumped from 1%, 3%, 5%, and 7% slopes.

	Coefficients	Standard Error	*t* Stat	P-values	Significant F	r^2
Intercept	2.79	0.43	6.54	0.00	0.0001	0.28
Erosion rate, g/s/m^2	0.04	0.03	1.37	0.18		

Table 3.3 Overall fits of shear stress equation to Yard waste compost, using data lumped from 1%, 3%, 5%, and 7% slopes.

	Coefficients	Standard Error	*t* Stat	P -value	Significant F	r^2
Intercept	2.32	0.36	6.45	0.00	0.176	0.03
Erosion rate, g/s/m^2	0.27	0.07	4.19	0.00		

Table 3.4 Results of regression analysis for shear stress model fit to combined data of Cecil soil and yard waste compost, using dummy variable representing slope change from Cecil soil to Yard waste compost

	Coefficients	Standard Error	*t* Stat	P-value	Significant F	r^2
Intercept	2.59	0.28	9.18	0.00		
Erosion rate, $g/s/m^2$	0.05	0.03	2.11	0.04	0.0011	0.12
Dummy for slope	0.18	0.06	2.98	0.00		

Table 3.5 Comparison of Cecil soil critical shears tress and erodibility parameters found in this study and determined by WEPP (1988).

Materials	Critical shear stress, Pa	Erodibility, $\times 10^{-3}$ s/m
This study	2.59	20.00
WEPP	4.45	3.84

Table 3.6. Correlation coefficient (r^2) and P-value of shear stress model fits for erosion on Cecil soil and yard waste compost

	r^2		P-value	
Slope	Cecil soil	Yard waste compost	Cecil soil	Yard waste compost
1%	0.26	0.45	0.09	0.02
3%	0.59	0.23	0.004	0.11
5%	0.59	0.37	0.004	0.04
7%	0.54	0.26	0.006	0.09

Table 3.7 Rill erodibility (K_r), critical shear stress (τ_c), and correlation coefficients (r^2) from shear stress equations for Cecil soil (CS) and yard waste compost (YWC) for each replication.

Slope		1 %			3 %			5 %			7 %				
Replications		1	2	3	1	2	3	1	2	3	1	2	3	Mean	Std.Dev
τ pa	CS	0.3635	0.5280	0.9197	1.4889	1.9389	1.4303	1.9942	3.1981	3.1839	2.8041	4.0495	2.7032	2.0447a	1.2441
	YWC	1.1922	0.8031	1.1997	3.0585	1.8618	4.6231	4.3575	4.0165	2.8355	5.6935	4.8459	6.8707	3.4651a	1.9807
D_r $g/m^2/s$	CS	0.0794	0.0868	0.1769	0.2895	17.5657	25.0079	0.8797	7.1200	2.3417	0.9685	25.5738	32.3844	8.8605a	13.4752
	YWC	0.6435	0.1515	0.8545	5.7398	2.3149	7.1547	5.3799	2.5849	1.8254	5.4844	3.9877	8.7251	3.7990b	3.2388
K_r Kg/s/N	CS	0.0031	0.0097	0.0340	0.0002	0.0028	0.0032	**-0.0001**	0.0049	0.0261	0.0022	0.0003	0.0082	0.0140a	0.0130
	YWC	0.0003	0.0005	0.0016	**-0.0029**	0.0012	0.0004	0.0023	0.0004	0.0013	**-0.0042**	0.0055	0.0021	0.0012a	0.00067
τ_c Pa	CS	1.4625	0.1211	0.6937	**-3.8000**	0.6196	2.4534	18.8333	**-1.1296**	1.4611	3.0833	**-1.6786**	1.3675	0.9517a	0.5574
	YWC	0.5326	0.3369	0.6969	5.2551	0.7840	**-13.4000**	1.9596	**-2.4900**	1.5530	6.9788	4.1172	2.7981	1.1167a	0.9226
r^2	CS	0.94	0.94	0.99	0.85	0.85	0.67	0.04	0.63	0.978	0.854	0.965	0.86	0.8065a	0.2644
	YWC	0.89	0.9	0.96	0.95	0.43	0.18	0.31	0.52	0.99	0.69	0.71	0.079	0.6332a	0.2856

Means for each performance measured with different letter designations are significantly different (probability ≤ 0.05).

Figure 3.1 Laboratory flume for study of soil and compost erosion under concentrated flow during erosion tests of Cecil soil (Photo by Xianben Zhu, April 24, 2006).

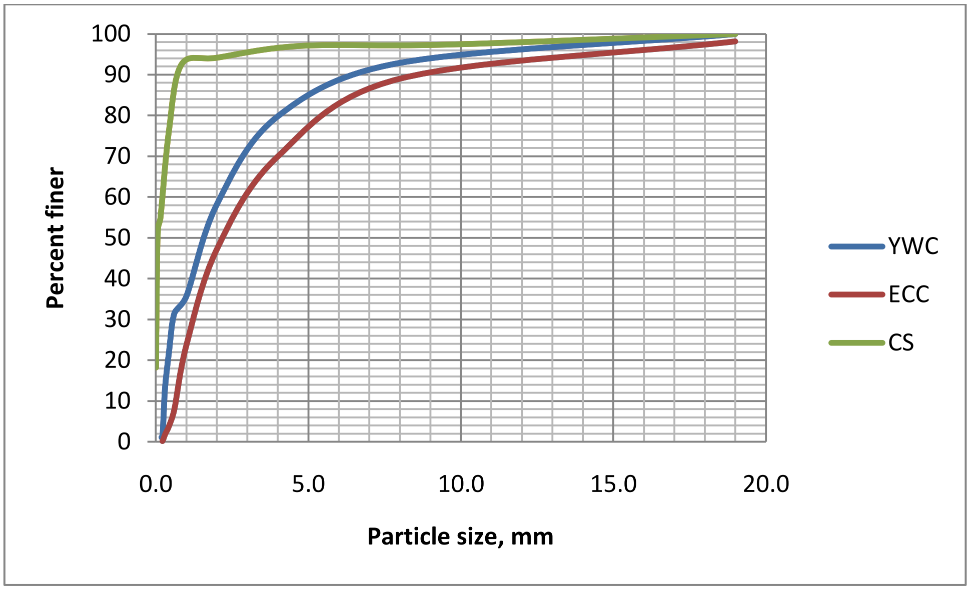

Figure 3.2 Cumulative particle size of Cecil soil (CS), yard waste compost (YWC), and erosion control compost (ECC).

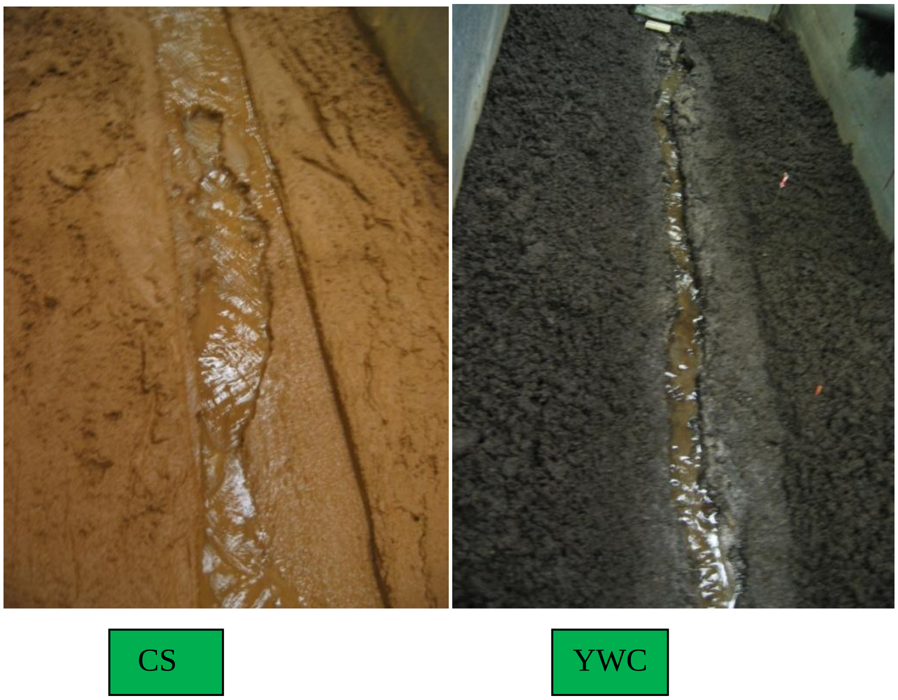

Figure 3.3 Rill erosion differences between Cecil soil (CS) and yard waste compost (YWC). Rills started downstream and with sidewall erosion, resulted in wide, shallow channels in Cecil soil. Rills started upstream, and with limited lateral erosion, resulted in narrow, deep channel in yard waste compost.

Figure 3.4 Micro-dams formed in an erosion control compost channel that blocked the flow and reduced velocity to cause infiltration and flow into the sides of the compost, resulting in the dispersal of the concentrated flow. The green color was due to a water tracing dye used to estimate channel average velocity.

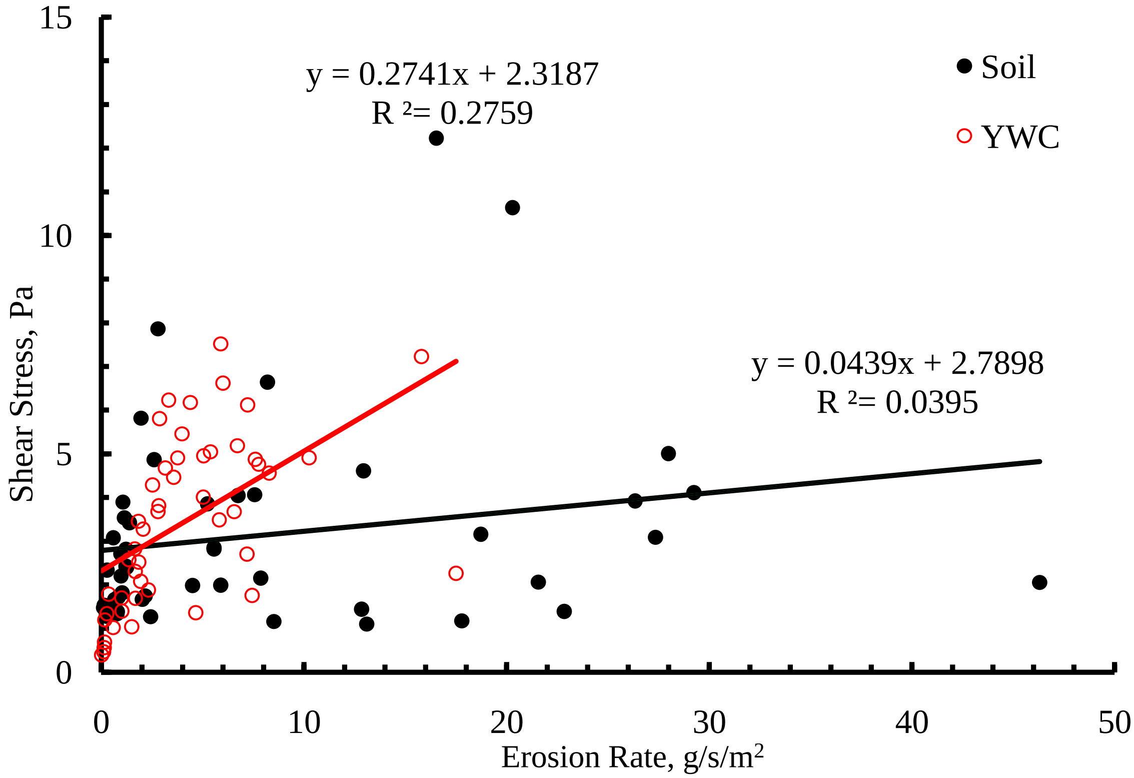

Figure 3.5. Overall fit of shear stress model to erosion on yard waste compost (YWC) and the Cecil soil, using the data of erosion derived from various slope levels. Results indicated that the critical shear stress values of yard waste compost and the Cecil soil were not significantly different.

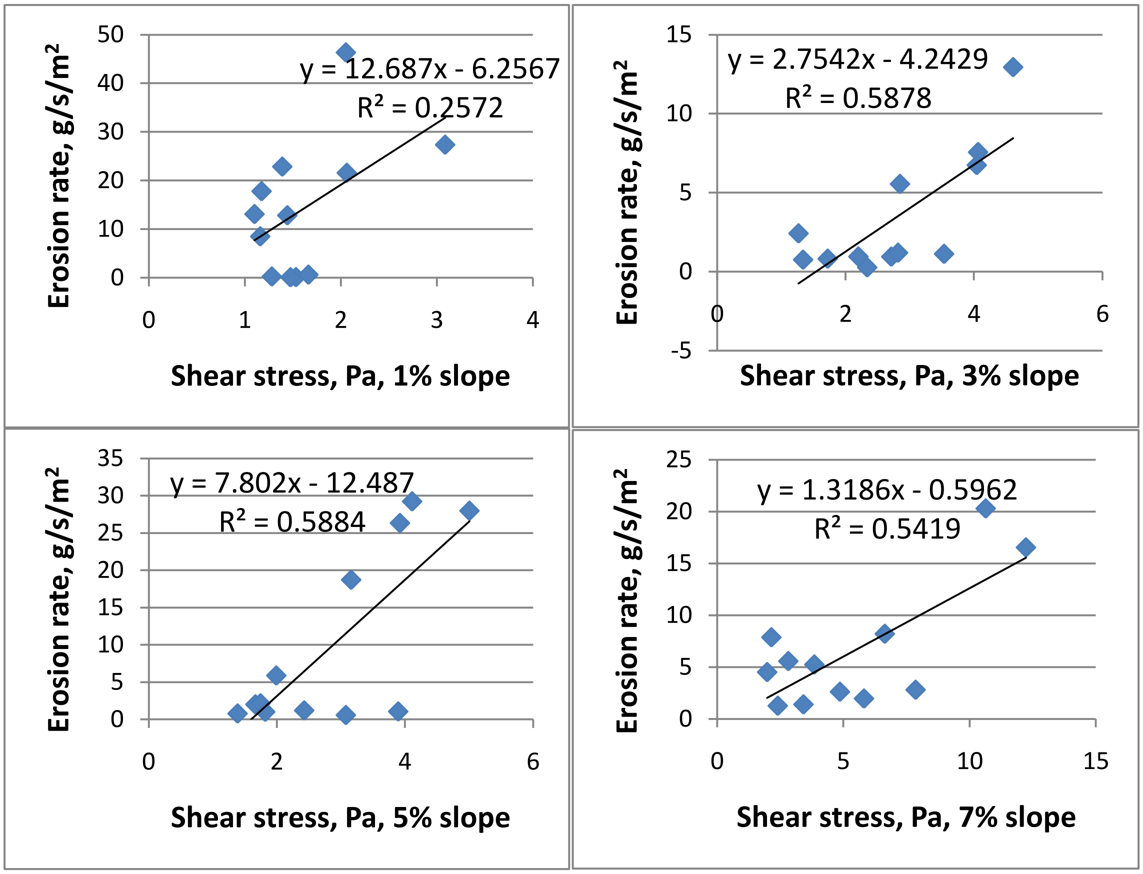

Figure 3.6 Shear stress equation for Cecil soil erosion subjected to concentrated flow on various slopes.

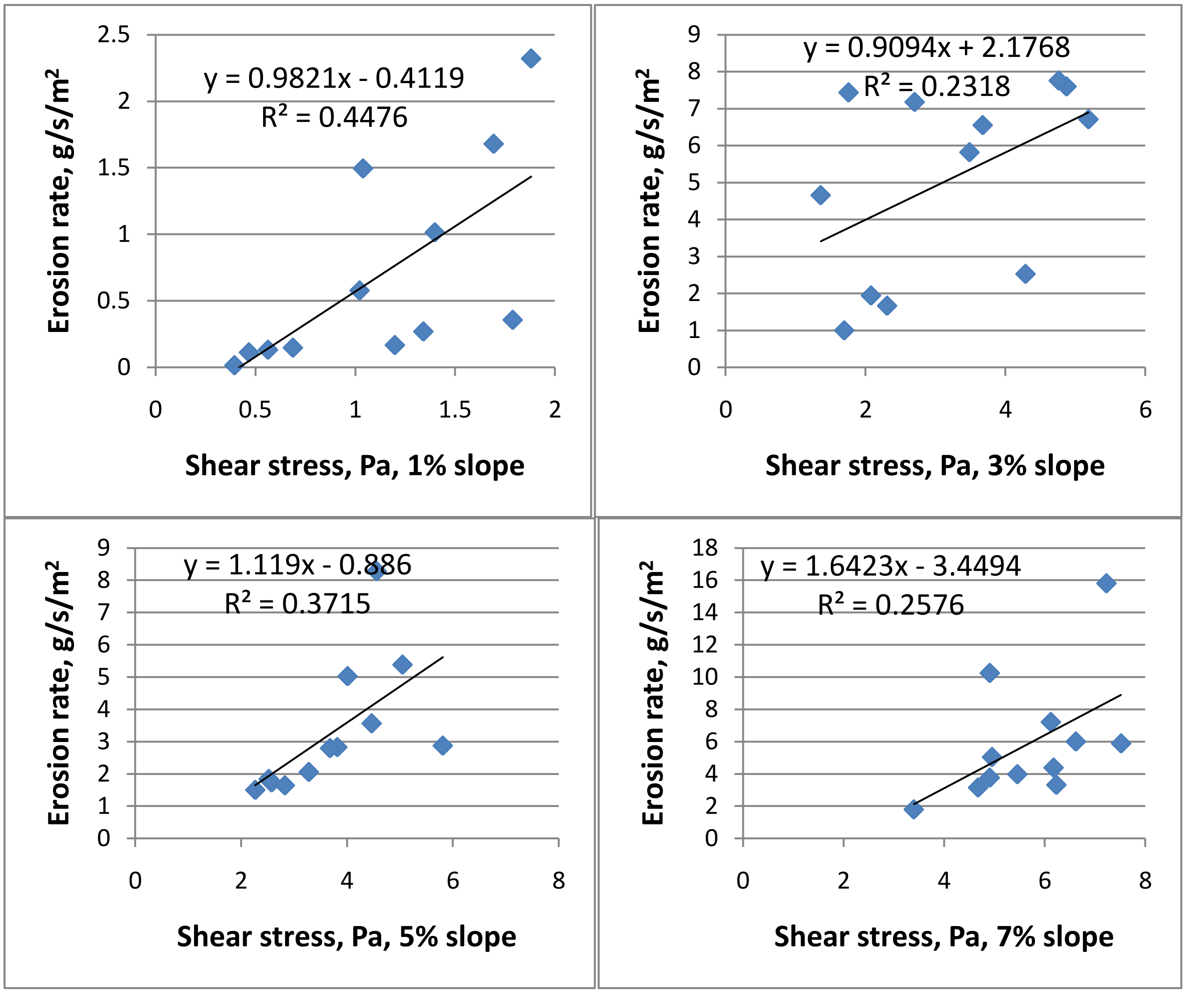

Figure 3.7. Shear stress equation for yard waste compost subjected to concentrated flow on various slopes.

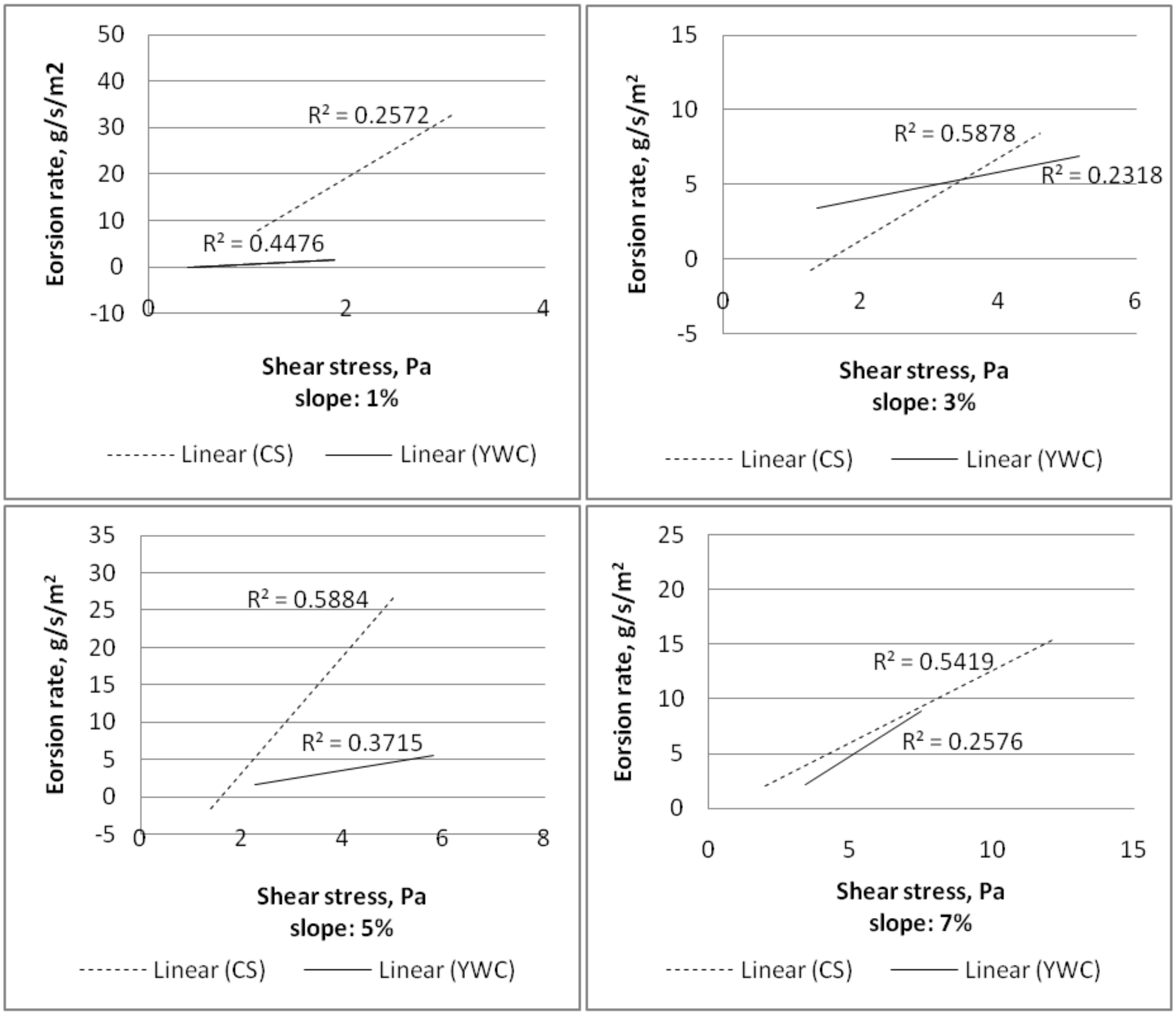

Figure 3.8. Comparison of shear stress equations for Cecil soil and yard waste compost on each slope.

CHAPTER 4

FIELD INVESTIGATION OF COMPOST BLANKETS FOR EROSION CONTROL UNDER CONCENTRATED FLOW CONDITIONS [2]

[2]Zhu, X. and M. Risse, Published in Transactions of the ASABE (2009), Vol. 52(1): 81-91, Reprinted here with permission of publisher.

Abstract

Compost blankets are recognized as an effective erosion control practice and have been utilized widely. While previous studies have proven that compost blankets can control erosion as well or better than traditional methods under normal rainfall and sheet flow conditions, little attention has been paid on how compost will respond to concentrated flow conditions. The objective of this research was to investigate erosion processes on compost blankets under concentrated flow conditions. Erosion control compost (ECC), yard waste compost (YWC) and a bare soil (BS, loam) were studied using four concentrated flow rates on 12.5 % slope plots. Time to initiate discharge, flow velocity, solids concentration, and total loss of solids were measured. The erosion process and rill evolution under these conditions were observed and recorded. Results indicated that the time elapsed to commence discharge from compost plots was significantly longer than from soil plots. Large amounts of inflow were able to infiltrate into compost matrix and flow through it, leaving a smaller portion of surface flow on compost plots than on soil plots. Under high inflow rates (2.7×10^{-4} m^3/s and 3.3×10^{-4} m^3/s), solids loss from compost plots was significantly less than those from soil plots. Under the same inflow conditions, average solids concentrations were significantly lower on compost plots than on soil plots as deposition occurred in compost rills. Deposited solids often formed micro-dams in the compost rills, which further promoted flow through the compost matrix and deposition of suspended particles. The formation of micro-dams on compost plots was an important mechanism of preventing soil erosion under concentrated flow conditions. Results of this study indicate that the erosion process on compost blankets may differ from classical shear induced rill erosion on soil surfaces. Future work will investigate models that may be used to better understand and predict erosion from compost blankets under concentrated flow conditions.

Introduction

Soil erosion is considered the biggest contributor to nonpoint source pollution in the United States according to the federally mandated National Pollutant Discharge Elimination System (NPDES) (USEPA, 1997). Morgan (2005) reported that soil erosion costs US $30 to $44 billion annually. Soil loss rates from construction sites can be 20 times that from agricultural lands. Soil erosion and sedimentation not only carry contaminants from upland areas, which can impair the water quality, but also threaten aquatic organisms by smothering essential aquatic habitats. The U.S. Environmental Protection Agency has recently released new regulations to control erosion and runoff from farms, construction sites, and roads in an effort to improve water quality (USEPA, 2008). The new regulations label land development as "point sources" requiring better erosion control practices and new permitting programs. The costs and impacts associated with soil erosion in developing areas are rapidly increasing due to urban sprawl lacking appropriate and effective soil erosion control. For this reason, many best erosion control and storm water management practices had been developed to reduce the impacts of soil erosion both from agricultural activities and urban development (Georgia Soil and Water Conservation Commission, 2000).

Advantages of Using Compost

Compost is the product resulting from controlled biological decomposition of organic material under aerobic conditions. It is sanitized through the generation of heat and stabilized to the point appropriate for a particular application. According to the US Compost Council (USCC, 1997), compost feedstock materials may include landscape trimmings, agricultural crop residues, manure, paper pulp, food scraps, wood chips and other biosolids. Compost materials have been primarily used as soil amendments, artificial topsoils, and growing mediums for the past two decades. Zhu and Wong (1987) investigated the effect of refuse and sewage sludge compost on crop growth and heavy metal content by mixing those materials with loamy sand at various ratios. They reported that crop yield in the compost treatment improved when compared to use of soil alone, and crops grown on compost-treated soils accumulated lower levels of heavy metals due to the high pH and organic matter content of compost materials. Research also indicates that application of compost materials improves soil properties. Compost can improve soil physical properties such as water holding capacity, total pore space, aggregate stability, temperature insulation and apparent soil density, and chemical properties such as pH, electrical conductivity, cation exchange capacity, and soil nutrient content (Hernando *et al*., 1989, Shiralipour *et al*., 1992, Risse *et al*., 2004). US EPA (1997) asserted that composts can be used to enhance turf grasses, enhance landscaping, and control plant disease. Singer *et al*. (2006) investigated the effects of compost on water retention and native plant establishment on a construction embankment, and concluded that compost materials could retain water and slowly release it, which improved vegetation development. Faucette *et al*. (2006) evaluated vegetative growth and soil quality affected by compost blankets and hydroseed application on soils disturbed by construction activities. They reported that the compost provided 2.75 times more vegetation and performed significantly better in preventing weed biomass than traditional hydroseed treatment. Enzo and Hogg (2008) suggested that application of compost can potentially reduce greenhouse gases.

Another benefit of using compost is to encourage the recycling of solid waste and organic material. The state of Georgia generates approximately 1.36 million metric tons of poultry litter, 1.81 million metric tons food processing waste, 2.26 million tons of wood waste and 362,000 metric tons of municipal biosolids annually (Risse *et al*., 2004). About 70 % of the solid waste generated in Georgia is organic and can be recycled and composted, and thus reused to improve soil properties and reduce soil loss. Furthermore, diverting these organic materials from landfills can reduce the potential groundwater pollution from landfill leaching, the amount of methane released to the atmosphere, and the need of constructing extra landfill sites.

Composted Materials Used for Runoff and Erosion Control

Application of compost as an erosion control practice has been widely studied and recognized. Stewart and Ettlin (1993) reported on a demonstration project using yard debris compost to control erosion, in which the compost layer absorbed large amounts of rainfall immediately after application and readily released nutrients into the soil. Storey *et al*. (1996) suggested the potential benefits of using compost as an erosion control practice include improved soil texture and structure, enhanced erosion resistance and vegetation establishment, and greatly reduced usage of landfill. The Integrated Waste Management Board in California investigated statewide projects on application of compost and concluded that green material compost was an excellent soil amendment for erosion control and revegetation of degraded soils (Claassen, 2000). Bresson *et al*. (2001) reported that municipal solid waste compost stabilized soil aggregates, delayed crust formation and seedbed slump, postponed runoff and reduced sediment concentration in the discharge.

A national specification for composted products used in erosion and sediment control has been developed and approved by the American Association of State Highway and Transportation Officials (AASHTO, 2007; Alexander, 2003). Glanville *et al*. (2004) reported a study comparing the concentration and total mass of nutrients and metals contained in runoff from compost blankets and conventionally treated highway embankments using simulated rainfall. They found that the total mass of most pollutants measured in runoff produced from compost treated plots were significantly lower than that in runoff from conventional treated plots. Risse *et al*. (2004) investigated the amount of runoff, erosion, and nutrient losses obtained from a variety of composts and mulch materials under simulated rainfall events. Results indicated that most of the treatments were effective in reducing total solids loss in the runoff. Manure composts increased infiltration and were effective in erosion control at a newly constructed road-right-of-way (Mukhtar *et al*., 2004) and increased the time required to initiate runoff (Ramos and Martinez, 2006) under simulated rainfall conditions. Persyn *et al*. (2004) verified that the compost utilized on a highway embankment could effectively reduce runoff rate and thus erosion based on their rainfall simulation study. Other studies (Harrell and Miller, 2005; Osorio and Juan, 2006) have proven that yard waste compost and urban solid waste compost could effectively prevent soil displacement and improve revegetation on roadside slopes.

Faucette et al. (2005) evaluated storm water from compost and traditional erosion control practices using three simulated rainfall events over a year and showed that compost treatments reduced the loss of total solids, total N and total P concentrations compared to the traditional practices. In another study comparing the erosion control effectiveness of compost blankets, straw with peptidylglycine alphaamidating monooxygenase (PAM), and mulch using both simulated or natural rainfall events, Faucette et al. (2007) concluded that soil loss from plots covered by compost blankets was significantly lower than that from plots covered by straw with PAM or mulch.

Current research on the use of compost for erosion control and storm water management has proven that compost blankets are effective at reducing runoff and interrill erosion. Compost blankets have been recognized as an erosion and sediment control best management practice (BMP) and used extensively, both on flat and steep slopes to control erosion. US EPA (2006) cautions against the use of compost blankets on areas where concentrated flow is likely to occur. However, with various sites and climate conditions in field, it is difficult to assure that concentrated flow will not occur on a compost blankets under various field conditions. Little guidance or research is available on the amount of concentrated flow that a compost blanket would be able to withstand. Persyn *et al*. (2005) investigated rill erosion on compost blankets, attempting to find relationships between mean shear stress and erosion rate for compost blankets. They used equation $\tau = \gamma RS$, where τ is mean flow shear stress acting on the plot, γ is specific water weight, S is energy slop, R is hydraulic radian ($R = \frac{A}{Wp}$, $A = \frac{Q}{V}$), Wp is wetted perimeter, A is across area of flow, Q is discharge and v is flow velocity. The authors suggested that the mechanisms that cause rill erosion on compost blankets might be similar to the mechanisms previously observed for unanchored crop residues (Foster *et al*., 1982). However, they showed that the relationship between mean shear stress and erosion rate was relatively weak and uncertainty was high due to floatation of compost particles on the water surface, the small size of test plots (0.2 m as plot width) which resulted in preferential flow along the plot boundaries, and movement of compost down the slope in bulk rather than as individual particles. That study suggested that the mechanisms controlling erosion in rills might be different for soils and compost, but additional studies have not been done.

The objective of this study was to investigate erosion processes on compost blankets under concentrated flow conditions.

Materials and Methods

Site Description

This research was conducted at the sediment control facilities in the erosion laboratory of American Excelsior Company (Fig. 4.1, Kelsey *et al*. 2005). The erosion laboratory is located at

Rice Lake/Barron county, Wisconsin, at 45°28'47" N latitude and 91°43'12" W longitude. The field experiment was conducted during the summer of 2007.

Two erosion control product-testing plots at the erosion lab were used. The geometric dimensions and profiles of these plots were constructed following ASTM standard methods (ASTM, 2007). The plots were constructed on 12.5 % embankment, 2.45 m (8 ft) wide and 10.7 m (35 ft) long. Soil profile of the plots is loamy sand on the surface 0 - 0.3 m (0 - 12 inches) over coarse sand 0.3 - 1.5 m (12 - 60 inches) according to the United States Department of Agricultural soil survey (USDA, 2008). Wood and Polyvinyl chloride (PVC) sheets were inserted into the soil for 0.1 m (3.9 inches) to form the plot border. Each original plot was divided into two subplots by trenching 0.1 m (3.9 inches) and installing wood borders into the soil along the middle of the plot. This created a total of four 1.22 m (4.0 ft) wide test plots (Figure 4.2). Prior to each run, the plot was prepared by adding soil to the plot to insure constant starting thickness, tilling up and down the slope using a Troy Bilt Bronco tiller; raking and smoothing the plot along the slope using a garden rake, and carefully compacting the top soil using a Wacker 1550 Plate Compactor run up and down the plot. Compaction was conducted to mimic post-construction conditions on highway embankments. Six numbered flags were then inserted on each side of plot at 1.5 m (4.9 ft) intervals along the plot’s border to serve as measuring stations. Water was obtained from a pond near the testing area and stored in a 500-gallon tank, from which it was pumped to the plot. A rotameter and check valves were used to regulate the inflow (Figure 4.2 and Figure 4.3). Solids content and density of the inflow water were measured. A flashing and receiving tank was installed at the toe of each plot to receive and store discharged runoff and solids. Compost materials were manually applied as 7.5 cm (3.0 inches) blanket layer over the entire area of the plot (USEPA, 2006). A 2.5 cm (1.0 inches) deep, 10 cm (3.9 inches) bottom width, and 15 cm (5.9 inches) top width trapezoidal channel was manually constructed along the center of compost blanket surface. This channel was constructed to direct the inflow and keep it concentrated on a 5cm thick blanket. This procedure was used by Elliot *et al*., (1989) in the development of water erosion prediction project (WEPP). A bunch of packed excelsior was placed on the top of pre-created channel to dissipate the energy of water where the flow was introduced into the plots. The compost blankets and soil in the plots were pre-wet by sprinkling water on the surface using a garden hose to wet the soil or compost surface prior to introducing concentrated flows (Figure 4.3). Four designed inflow rates (1.3×10^{-4}, 0.2×10^{-3}, 2.7×10^{-4}, 3.3×10^{-4} m^3/s or 8, 12, 16 and 20 L/min) were applied on each of the materials. These flow rates were determined based on trail runs that attempted to determine the approximate points where rill erosion was initiated and when erosion became so excessive that it would be difficult to complete a run. Three repetitions were conducted on each treatment, using a completely randomized design.

Treatments

Materials used in this experiment included yard waste compost (YWC) and erosion control compost (ECC) purchased from White Oak Farm in Oconomowoc, Wisconsin, which is an US Composting Council seal of testing assurance program sealed company. The feedstock of YWC was yard waste, and the ECC contained yard waste compost and coarse ground wood waste. Our intention was to compare a yard waste compost blanket with an erosion control compost (ECC) blanket which met the national specifications (USEPA, 2006, Alexander, 2003). However, neither of the composts received on the site actually met the national specifications for an ECC in term of particle size. Even though it did not meet the specification of erosion control, the cumulative particle size distribution showed that the ECC had coarser particles compared to

B

YWC (Figure 4), which has been shown to be a significant factor for erosion control compost blankets (Faucette, 2007). Local loamy bare soil (BS) was used as control in this project; its cumulative particles size distribution is shown in Figure 4.4.

Basic physical and chemical properties of compost materials were measured by Energy Laboratories, INC. at Casper, WY (Table 4.1) and showed the nutrient content, organic matter, and pH values of the composts met national specifications for erosion control compost blankets (USEPA, 2006). The particle size of compost materials was determined at the erosion lab, using 300 g dried subsamples based on the Test Methods for the Examination of Composting and Compost (USCC, 1997). Size of sieve opening included 6.35, 2.38, 1.4, 0.84, 0.6, 0.425, 0.3, 0.25, 0.212 and 0.18 mm.

Moisture Content Measurement

Compost and soil samples were collected at flags 1, 3 and 6 beside the pre-created channel for moisture content measurement before and after each run. The compost samples were collected from the compost blanket surface to the soil interface and after sampling the cored holes were filled with additional compost. Soil samples were collected at the same spots where compost samples were collected to the depth of 5 cm. Compost moisture content was determined gravimetrically, by measuring the sample weight before and after oven drying at 105 ℃ for 1.5 h, following the method recommended by the USCC (1997). Soil moisture content was determined following ASTM D4643-00 standard test method for determination of water (moisture) content of soil by the microwave oven method (ASTM, 2000).

Flow Velocity and Rill Width Measurement

The surface flow velocities on plots were measured using leading edge technique as described by Elliot *et al*. (1989) and Persyn *et al*. (2005). A dye was injected at point one and the time over which the dye traveled to point six was recorded, the dye travel distance was 7.62 m. This measurement was conducted in 3-min intervals. Mean surface flow velocity for each run was obtained by averaging the seven measurements. A factor of 0.7 was used to convert the mean surface flow velocity measured with the dye to a mean flow velocity for each run based on the work of Elliot (1989).

Rill widths along the pre-created channel bed were measured using a ruler on the seven sections created along the plot. Within each section, three critical points were chosen at which rill widths were measured. The critical points were defined as the points that represented major changes of the rill width within a section. The rill widths were measured at the water surface in the rill and these measurements were conducted at 3-min intervals.

Discharge and Solids Loss Analysis

Discharge rate from the plot was determined by recording the time required to fill a 3.79 liter (one gallon) bucket. The measurement was conducted at 3-min intervals throughout each run. The first sample for each run was collected to determine the discharge and solids concentration at first flush. The total amount of discharge for a run was determined by multiplying the average discharge rate by the period of flow, which was set as 21 min. The run time of 21 min was determined based on trial runs that indicated steady conditions were achieved within this time period. Sediment samples were collected in 500 mL bottles at 3-min intervals. Samples were weighed, filtered using Whatman filter paper 410 and oven dried at 105 ℃ until constant weight was achieved. Dry weight of bottles and filter papers were subtracted to determine the solids weight of each sample. Discharge density of each sample was determined by dividing the sample mass by the volume (500 mL). Mean solids concentration for a particular run was determined by averaging the solids content of the discharge samples. The first discharge sample of each run was reported separately and not used for mean solids concentration calculation because the first sample often contained a large amount of light material from the plot surface and did not represent steady state flow conditions. However, the solids contents of first samples, or first flushes, were determined and used for total solids loss computation. The total solids loss for each run was determined by summing the solids loss from both the first flush and the consecutive steady state flows.

Statistical Analysis

SAS version 9.1 (SAS, 2002) was used for statistical analysis. Separation of means was determined by using ANOVA procedure. Duncan's Multiple Range tests were used to determine any significant differences between treatments at $\alpha = 0.05$.

Results and Discussion

Moisture Condition

Initial moisture content for ECC blankets is important because it influences the capacity of the blanket to absorb overland flow. Since the plots were pre-wet, significant differences in initial moisture contents for each run of an individual material were not expected. Results showed no significant differences among the four runs for YWC and BC. For ECC, significantly higher initial moisture content was observed for the 3.3×10-4 m3/s (20 L/min) inflow run than the other runs on this material. This was probably due to a storm event that occurred on the day before the test. The final moisture contents of both composted materials were significantly greater than the final moisture content of soil under all inflow conditions (Table 4.2), indicating the higher water holding capacity of composted materials relative to soil.

Time Required to Initiate Discharge at the Plot Outlet

Both ECC and YWC had significantly longer periods of time to commence discharge compared to the bare soil at low inflow rates (1.3×10^{-4} and 0.2×10^{-3} m^3/s or 8 and 12 L/min). At high inflow rates (2.7×10^{-4} and 3.3×10^{-4} m^3/s or 16 and 20 L/min), ECC showed no significant difference from BS regarding the time to initiate discharge, while YWC significantly delayed the discharge for all inflow rates compared to the bare soil. Both ECC and YWC had significantly longer periods of time to initiate discharge at 1.3×10^{-4} m^3/s (8 L/min) compared to the rest of the inflow rates (Figure 4.5). The longer time to initiate runoff on the compost plots could be due to several factors. First, flow velocities on the plot surface were normally lower for compost plots and lower inflow rates, which allowed more time for the compost to absorb a greater portion of the flowing water. The low flow velocity at the surface also allowed more time for water to infiltrate vertically and laterally into the plot matrix. Under higher inflow rates, a greater amount of water was observed on the blanket surface and part of it reached the plot's outlet before it could percolate and be absorbed by the compost. Finally, larger particles in the compost blankets created a higher percentage of pore space in the compost matrix than in soil matrix, which allowed more water to flow through it, resulting in a longer time to initiate discharge for compost plots than soil plots.

Erosion Process and Rill Evolution

Head cut and rill bed scour were the primary erosion mechanisms on both soil and compost plots. However, the temporal and spatial evolutions of rills were different on the soil and compost plots (Figure 6 and 7). Under the 1.3×10^{-4} m^3/s (8 L/min) inflow condition, surface flow was not present on YWC plots during the experimental period; whereas on ECC plots, surface flow was observed only during the last 3 min of the run. This absence or delay of surface flow on the compost materials indicated that significant infiltration and subsurface flow occurred through the compost matrix. The average rill width on both compost plots seemed relatively constant with the time elapsed (Figure 4.6); however, the actual rill width along those plots was more variable than the rill width on soil plots under the inflow rates of 0.2×10^{-4}, 2.7×10^{-4}, 3.3×10^{-4} m^3/s (12, 16 and 20 L/min) (Figure 4.7). The morphological topography of the rills formed on compost plots under higher inflow rates indicated that complex erosion and deposition process frequently occurred. Head cut at the upstream part of the slope was the major source of the solids carried by the flow. These particles were often deposited in the channel bed as larger macro pores allowed a portion of water to flow through the compost matrix. The deposited particles inter-locked together and trapped the suspended solids flowing downstream; thus the deposition accumulated quickly to form a "micro-dam" across the pre-created channel. This micro-dam blocked the flow and encouraged additional water to filter through the compost. The transport capacity of the runoff decreased as the velocity dropped when flow approached a micro-dam, resulting in more deposition of suspended solids. As the amount of water ponded behind the micro-dam increased, either the flow would scour a new channel through the compost or the micro-dam would eventually blow out under the pressure of the ponded water. Either way, the velocity would suddenly increase and compost particles would be eroded rapidly by local turbulence. Once a micro-dam blew out, the clean water ponded behind the micro-dam had excessive transport capacity and carried many particles downstream. Another micro-dam would quickly form somewhere downstream as the aforementioned process repeated itself. The lower the inflow rates, the greater and more stable the micro-dams would be allowing longer time for water to flow through the compost matrix. Figure 4.8 illustrates the forming and breaking of a micro-dam on an ECC plot under 0.2×10^{-4} m^3/s (12 L/min) inflow. Pictures A and B in Figure 4.8 show the processes of solids accumulation on a compost rill and the formation of micro-dams. As solids accumulated, water was ponded by the micro-dams and infiltrated into the channel sidewalls. Pictures C and D showed the evidence that surface flow advanced by breaking the micro-dams and changing its flow path. It was clear that micro-dams were reestablished downstream and the processes of forming and breaking of micro-dams was repeated.

While the process of micro-dams forming and breaking occurred on the compost plots, the soil channel did not exhibit this phenomenon. The erosion process and width of the rill on soil plot was relatively stable (Figure 4.7). Most of the soil particles eroded at the upstream of the channel was delivered to the plot outlet with a small portion of them deposited near the plot outlet due to reduced flow velocity. This caused the width of flow to increase on soil plots increased when water approached the outlet (Figure 4.7). On the soil plot, there was a trend toward scouring and incision of the rill over time resulting in concentrated flow and deeper, incised rills (the depth of the rills were not measured but this was an observation) (Figure 4.6).

Three reasons potentially explain why the micro-dams often formed on the compost plots but not on soil plot. First, at a given flow transport capacity, a greater volume of compost particles than soil particles were entrained and carried by the flowing water as compost materials had lower bulk density than the soil. Second, the flow through the channel walls was greater in the compost than the soil due to the presence of more macro pores. Third, the greater particle size and distribution of particles across the size range of the compost material allowed these particles to interlock across the rill and hence trap and filter more particles that are carried by the flowing water.

Scouring in the rill was significant for both compost and soil plots. The entrained solids from the soil channel bed were delivered downstream to the outlet. Once a rill was formed on a soil plot, the clean water from upstream continually scoured the channel, resulting severe erosion in the soil channel. Scouring of rills was observed on compost plots and soil layer was occasionally exposed to the flow under the high inflow conditions. Once this occurred, it would also begin eroding; however, three major mechanisms kept most soil particles from leaving the plot with discharge. First, the micro-dams trapped soil particles; second, the reduced velocity encouraged deposition of suspended solids; and third, the macro pores of the compost blanket encouraged lateral flow that which diverted the flowing water and reduced shear stress of the flow.

Flow Velocity

Flow velocity is a key factor affecting soil erosion as it impacts transport capacity and shear stress of the flowing fluid ($\tau = \gamma \times R \times S$, $R = \frac{A}{W_p}$, $A = \frac{Q}{V}$). A higher flow velocity indicates both higher transport capacity and erosive potential. While the velocity on the soil plot was easily measured using a dye tracer as the water flowed on the surface; the velocity on the compost plots was often difficult to measure due to the formation of micro-dams along the artificial channel that detoured or disconnected the flow. Velocity decreased near micro-dams while rapidly increasing in the areas where micro-dams failed. Under low inflow conditions, surface flow disappeared as all the water infiltrated into the compost matrix, resulting in no runoff to measure velocity. In this study, the surface flow velocity on the compost plot was measured wherever surface flow was present and then the segmented surface velocities were averaged for mean surface flow velocity. However, these velocity values were not used for shear stress estimation because they could not represent the velocity under a steady state flow condition, which is a key assumption for shear tress computation (Elliot *et al*., 1989).

In the case of 1.3×10^{-4} m^3/s (8 L/min) inflow rate, no surface flow was observed on the entire length of the YWC plots as all of the water flowed through the compost matrix (Table 4.3).

The velocity of surface runoff on ECC plots could be detected but was significantly lower than that on soil plots. The flow velocities were not significantly different for YWC and ECC when inflow was increased to 0.2×10^{-3}, 2.7×10^{-4} or 3.3×10^{-4} m^3/s (12, 16 or 20 L/min), suggesting that the process of micro-dams forming and breaking were similar on both types. The velocity on the soil plots showed no difference as inflow changed from 1.3×10^{-4} to 3.3×10^{-4} m^3/s (8 to 20 L/min). This was probably because the flow was relatively stable in the soil channel, and it reached a terminal velocity (0.27 m/s) for this loamy soil at a 12.5% slope.

Discharge at the Plot Outlet

Discharge is a crucial parameter for estimating the surface flow, which contributes to shear stress estimation in a rill. The difference between discharge rate and inflow rate is a good indicator of infiltration and water holding capacity of the materials on the plots.

On compost plots, discharge took longer time to begin and was lower than the soil plots (Figure 5). The discharge was 8.5×10^{-5} m^3/s (5.07 L/min) from YWC and 8.3×10^{-5} m^3/s (4.97 L/min) from ECC compared to 1.2×10^{-4} m^3/s (7.07 L/min) from BS under a 1.3×10^{-4} m^3/s (8 L/min) inflow condition. The loss of water from inlet to outlet was 36.61% for YWC, 37.94% for ECC, and 11.62% for bare soil (Table 4.4). The significant difference of discharge and water loss between compost plots and bare soil plots reflected the function of mircro-dams which ponded the water and allowed greater amount of time for the water to move vertically as well as laterally. Under the higher inflow conditions 0.2×10^{-3}, 2.7×10^{-4}, and 3.3×10^{-4} m^3/s (12, 16, and 20 L/min), there were no significant differences among the three materials for discharge or water loss, however, there was a trend toward more water loss on the compost plots.

Solids Concentration and Total Solids Loss

The solids concentrations of discharges were measured at 3 min intervals. The average solids concentration of a single run was calculated by averaging all of the individual measurements for a given flow rate, excluding the first flush. The first flushes were excluded because they were not representative of steady-state flow conditions. The solids concentrations of the first flushes were measured and reported.

The solids concentration of the first flush from the compost plots were significantly lower than those from soil plots at the $1.3 \times 10^{-4} m^3/s$ (8 L/min) inflow rate, confirming the observation that no or little surface flow occurred on the YWC and ECC plots under that condition. Under this condition, the solids in the first flush from compost plots were those particles that were drawn out by upward movement of water in the compost blanket near the outlet. This process effectively filtered the soil particles and prevented them from leaving the plot. The solids concentration of first flush from ECC plots was increased when inflow rates were increased from 1.3×10^{-4} to 3.3×10^{-4} m^3/s (12 to 20 L/min), but no significant differences with those from soil plots were found. This increase was probably due to the greater amount of compost particles that were washed away by the larger inflow rates, which resulted in exposure and erosion of soils at several spots on compost surface. The average solids concentration from both YWC and ECC compost plots were less than those from soil plots under all inflow rates, which confirmed the effectiveness of particle trapping and filtering of the micro-dams formed along the compost plots.

The total solids loss for each run was calculated by summing the amount of solids lost from first flush and from the following flows. Under the low inflow conditions (1.3×10^{-4} and 0.2×10^{-3} m^3/s or 8 and 12 L/min), no statistical differences of solids loss from composts and soil were observed, which was probably due to the lack of significant rill erosion on the soil plots under inflow conditions. There was significantly greater amount of solids lost from soil plots than from compost plots under high inflow conditions (2.7×10^{-4} and 3.3×10^{-3} m^3/s or 16 and 20 L/min), which indicated the effectiveness of composts in alleviating the severity of channel scouring and incision (Figure 4.9 and Table 4.4). Under the high inflow conditions, micro-dams were formed on the compost plots and quickly blew out by the inflowing water behind them. At the end of the runs with high inflows, undisrupted rills were often formed along the plot, either inside or outside the pre-created channel, leaving soil layer exposed to the flows as the compost materials were eroded away in the rills. Besides scouring downwardly to the soil layer, a portion of water in the rills flowed laterally into the sidewalls as the compost materials had greater amount of pore space that allowed water to flow through it easily. Under the same inflow conditions, the amount of water flowing in the compost rill was reduced by the aforementioned processes, therefore, the shear stress acting on the soil layer underneath a compost blanket was much less than the shear stress acting on the soil layer in the soil plots resulting in a smaller amount of solids loss from compost plots compared to soil plots.

Conclusions

A field experiment was conducted to determine rill erosion processes and solids loss from yard waste compost and erosion control compost and a bare soil. A significantly greater amount of time required for compost plots to initiate discharge at plot outlet than for soil plots indicated the improved ability of compost materials to hold or divert water compared to bare soil. This result was verified by water balance measurements that indicated that the compost plots retained more water. The process of rill evolution on compost plots presented a characteristic of micro-dams forming and encouraging filtering and deposition, which was the primary mechanism for preventing soil erosion. Through the formation of micro-dams, the entrained soil particles were trapped and deposited along the compost plots, resulting in less delivery of soil particles from upstream to the plot outlets. Micro-dams formed along the compost plots diverted the flow into the compost matrix, which greatly reduced flow velocity and thus decreased shear stress acting on the plot. Both types of compost showed significant reductions in solids loss compared to bare soil under the higher inflow conditions (2.7×10^{-4} and 3.3×10^{-3} m^3/s or 16 and 20 L/min) showing their effectiveness of controlling the flow induced soil erosion.

This study showed that the primary mechanism for compost blankets' ability to reduce soil erosion under concentrated flow conditions were micro-dam formation and filtering through the compost matrix. While the intention was to apply the shear stress model to develop design aids for using compost blankets, constant shear stresses could not be maintained on compost plots so the model was not applicable. Future studies will focus on testing the effectiveness of different compost materials, especially those meet the physical requirements of national specifications for erosion control compost blankets, under concentrated flow conditions so that design aids can be developed for site design and installation using compost blankets for slope erosion control. Moreover, future research should evaluate the potential and effectiveness of compost materials as liners to protect open channel beds.

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Table 4.1. Properties of compost materials, % dry weight basis

Parameters	ECC	YWC
Total Nitrogen (%)	1.57	1.9
Phosphorous (as P_2O_5)(ppm)	0.52	0.28
Potassium (as K_2O)(ppm)	1.05	0.49
Calcium (Ca)(ppm)	5.7	4.7
Magnesium (Mg)(ppm)	2.14	1.5
Organic Matter Content (%)	39	44.4
pH (standard unit)	8.01	7.71

Table 4.2 Average initial and final moisture content of erosion control compost, yard waste compost and bare soil (3 replications).

Inflow rate, $10^{-4}m^3/s$	**Erosion Control Compost**		**Yard Waste Compost**		**Bare Soil**	
	Initial MC ± σ * (%)	Final MC ± σ (%)	Initial MC ±σ (%)	Final MC ± σ (%)	Initial MC ± σ (%)	Final MC ± σ (%)
1.3	17.65h ±5.39	24.20fghi ±5.66	27.56def ±1.45	37.70ab ±2.81	10.13k ±0.72	18.84hij ±1.05
2	19.81ghij ±3.89	25.81efg ±4.80	28.89def ±6.10	39.13 a ±3.26	10.46k ±0.29	18.25ij ±0.57
2.7	25.09efgh ±5.20	30.79cde ±5.16	30.60cde ±1.92	40.14 a ±2.82	9.14 k ±0.53	19.18hij ±2.45
3.3	29.68 def ±2.25	36.16abc ±3.67	32.64bcd ±5.02	40.57 a ±2.60	9.72k ±0.54	19.19hij ±1.11

[a] MC: Moisture Content; σ: Standard deviation . Values within a column or row followed by the same letter are not significant difference at α = 0.05 using Duncan's Multiple Range test (n = 9 for each measurement).

Table 4.3 Average flow velocity, discharge and percent loss of the water from inlet to outlet for yard waste compost, erosion control compost, and bare soil under various inflow rates.[a]

Inflow rate, $10^{-4} m^3/s$	Material	Average flow velocity, m/s	Discharge, $10^{-4} m^3/s$	Percent loss of water from inlet to outlet, %
1.3	YWC	- -[b]	0.85 e	36.61a
	ECC	0.14b	0.83 e	37.94a
	Bare Soil	0.26 a	1.18 d	11.62bc
2.0	YWC	0.21 ab	1.44cd	28.02abc
	ECC	0.20 ab	1.63 c	18.35abc
	Bare Soil	0.27 a	1.82 c	8.89bc
2.7	YWC	0.20 ab	2.50 b	6.23c
	ECC	0.28 a	2.28 b	14.16bc
	Bare Soil	0.26 a	2.51 b	6.03c
3.3	YWC	0.21 ab	3.09 a	7.38bc
	ECC	0.29 a	2.71 ab	18.78abc
	Bare Soil	0.27 a	3.10 a	7.06bc

[a] Values followed by same letter in a column are not significantly different at $\alpha = 0.05$ using Duncan's multiple range test (n = 21 for each measurement).

[b] no data was available.

Table 4.4 First flush solids concentration, average solids concentration, and total solid loss from the three materials under four inflow rates.[a]

Inflow rate, 10^{-4} m^3/s	Material	First flush solids concentration ± σ (g/kg)	Average solids concentration ± σ (g/kg)	Total solids loss ± σ (kg)
1.3	YWC	3.63f ±2.83	2.52e ±1.73	0.24c ±0.18
	ECC	15.75ef ±13.52	40.78bcde ±42.46	5.91c ±7.14
	Soil	92.82de ±32.87	72.93a ±23.52	11.99bc ±2.57
2.0	YWC	48.66def ±75.83	3.66de ±2.35	0.79c±0.58
	ECC	15.75ef ±16.95	24.44cde ±17.44	5.76c ±5.08
	Soil	134.95bcd ±31.80	54.54b ±6.04	13.32bc ±1.12
2.7	YWC	10.10ef ±10.79	13.07de ±5.92	4.35c ±2.08
	ECC	237.23ab ±52.94	28.9cde ±11.92	8.66bc±3.42
	Soil	204.28abc ±98.56	95.75a ±26.84	35.48a ±12.61
3.3	YWC	120.46cde ±109.00	43.10bcd ±26.49	20.95b ±15.81
	ECC	286.34a ±14.79	30.60cde ±12.33	11.67bc ±4.78
	Soil	221.69abc ±104.07	106.13a ±27.40	46.79a ±12.63

[a] Values followed by the same letter in a column or row are not significantly different at α = 0.05 using Duncan's multiple range test (*n* = 21 for each measurement).

Figure 4.1 Aerial photo of the site where this project was conducted. Soil survey (USDA, 2008) shows the soil at that site is loamy sand at 0 to 0.3 m (0 to 12 in.) and coarse sand 0.3 to 1.5 m (12 to 60 in.).

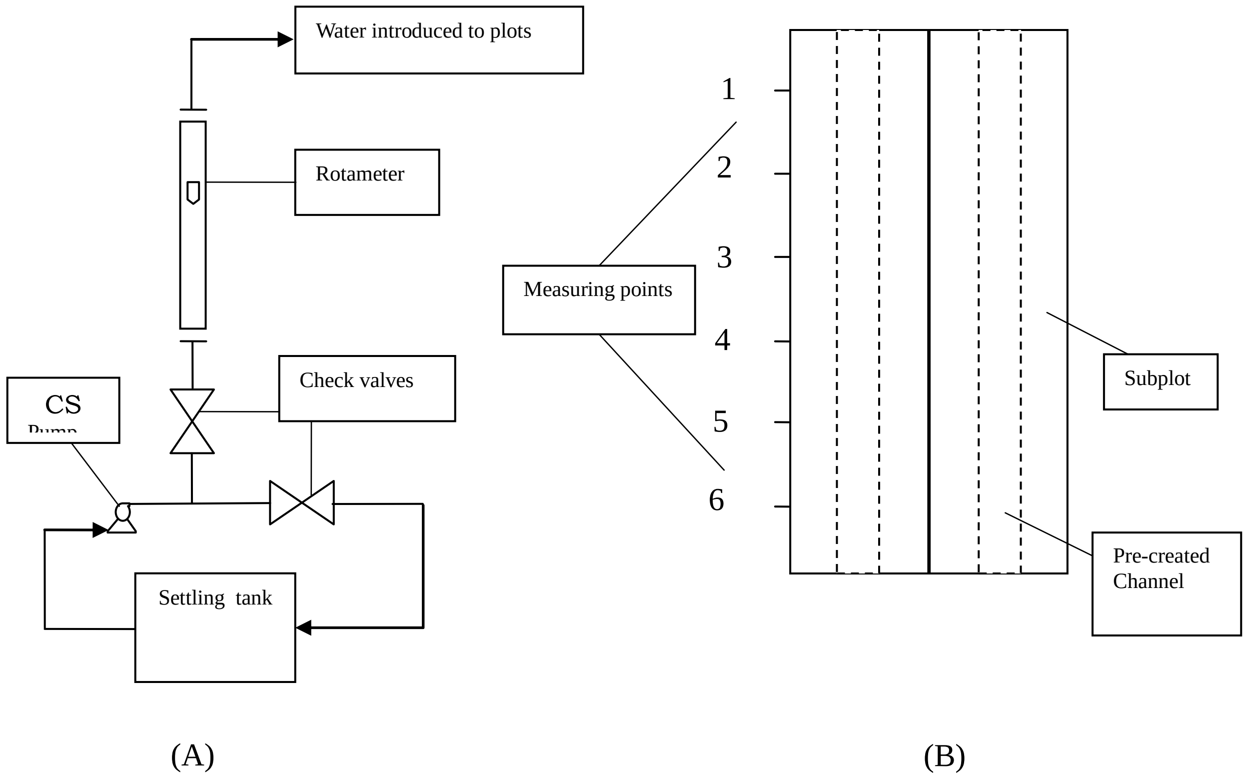

Figure 4.2 Schematic of (A) Inflow station and (B) Plot layout

Figure 4.3 Pictures of (A) inflow section and (B) testing plots.

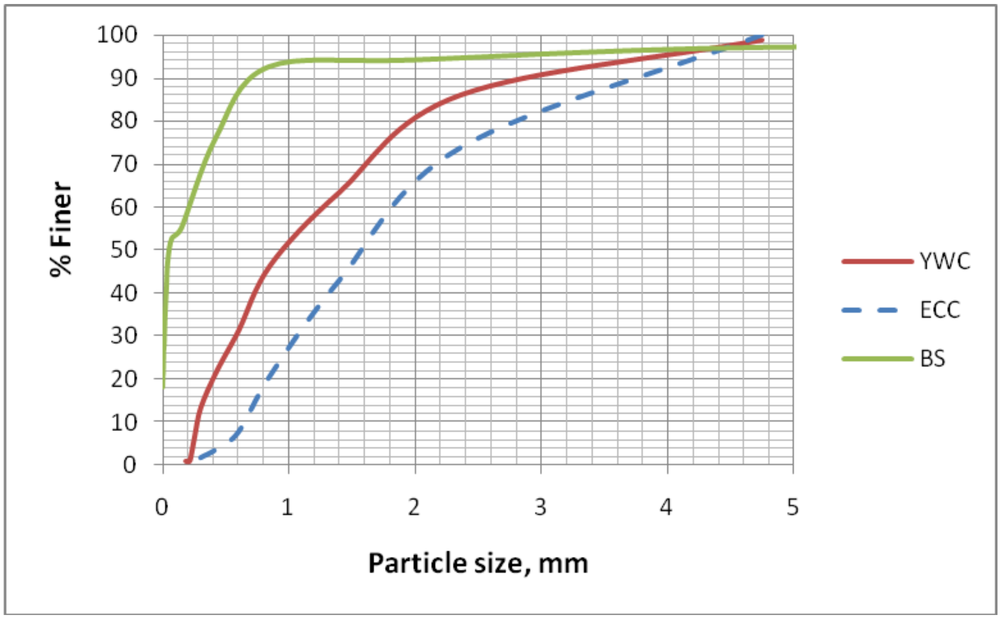

Figure 4.4 Cumulative particle size of control bare soil, yard waste compost, and erosion control compost (D_{50BS} = 0.049 mm, D_{50YWC} = 0.97 mm, and D_{50ECC} = 1.6 mm).

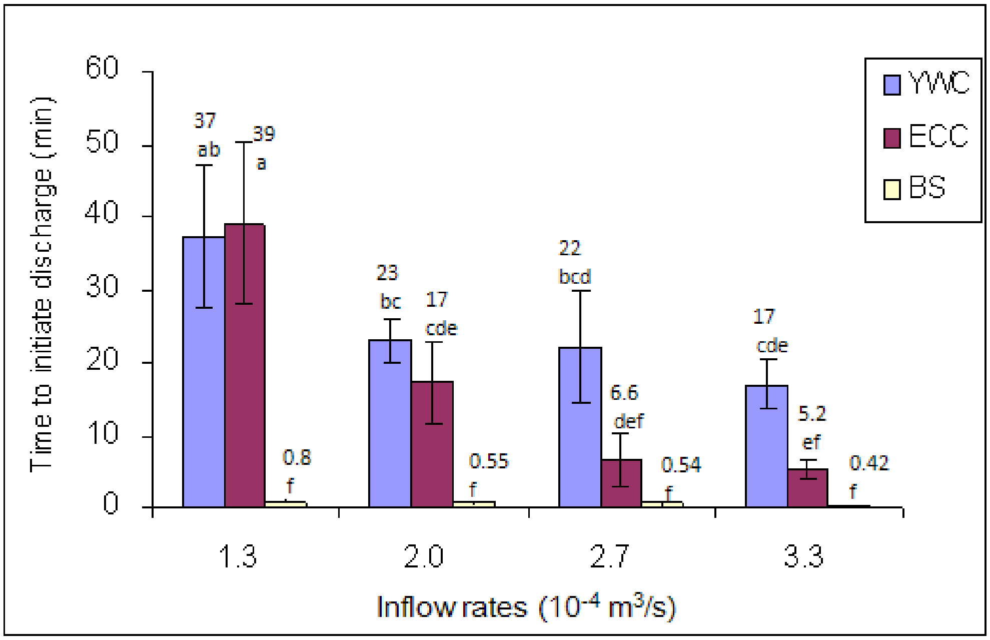

Figure 4.5 Mean and standard deviations of time to initiate discharge on the three plots under four inflows. Values on the top of bars with same letters were not significantly different at α = 0.05 using Duncan's multiple range tests (n = 3 for each measurement).

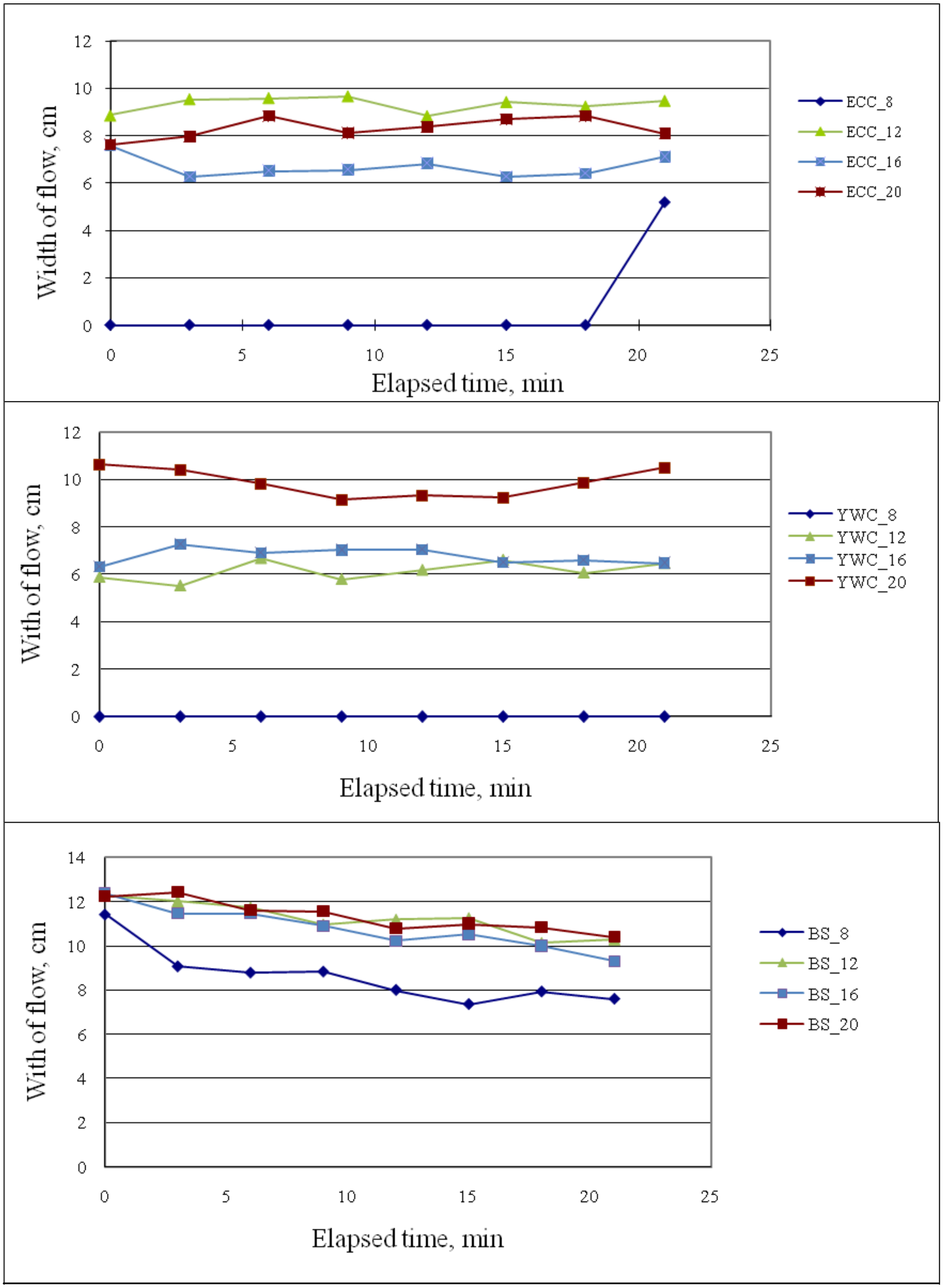

Figure 4.6. Evolution of the average rill width with time elapsed on the three types of plots with various inflow rates (measurements were conducted at the seven sections along the plots; 8, 12, 16, and 18 stand for the inflow rates, in unit of L/min, equating to 1.3, 2.0, 2.7, and 3.3 10^{-4} m^3/s).

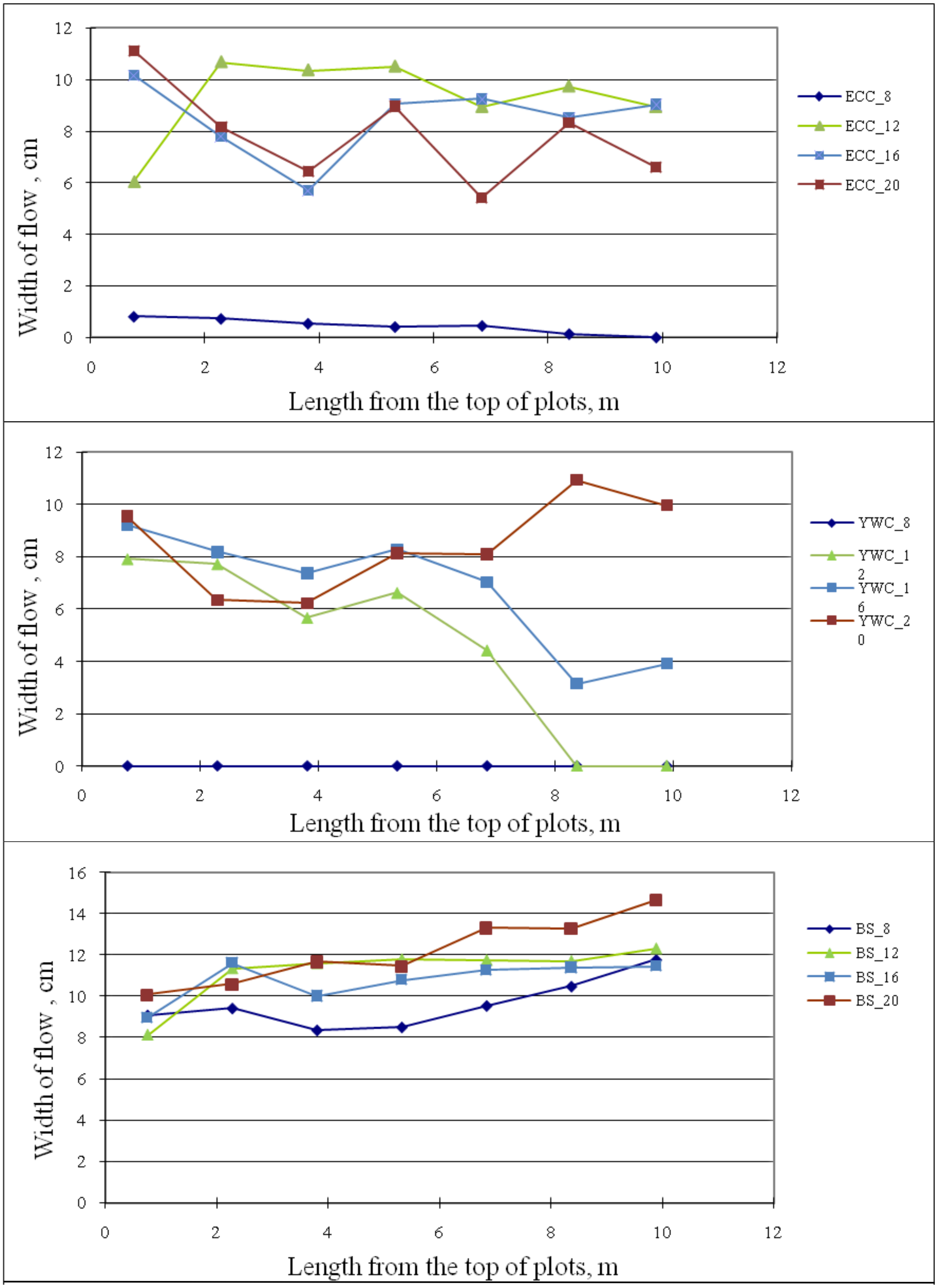

Figure 4.7. Evolution of the average rill width with plot length for the three types of plots at various inflow rates (measusrements were conducted in 3 min interval for 21 min flow events; 8, 12, 16, and 18 stand for the inflow rates, in unit of L/min, equating to 1.3, 2.0, 2.7, and 3.3 10^{-4} m^3/s).

Figure 4.8. Pictures showing the micro-dams: (a) micro-dam formed across the pre-created channel, (b) micro-dam grows as solids accumulate behind it, (c) micro-dam blows out allowing flow to advance, and (d) new micro-dam was formed, encouraging more infiltration.

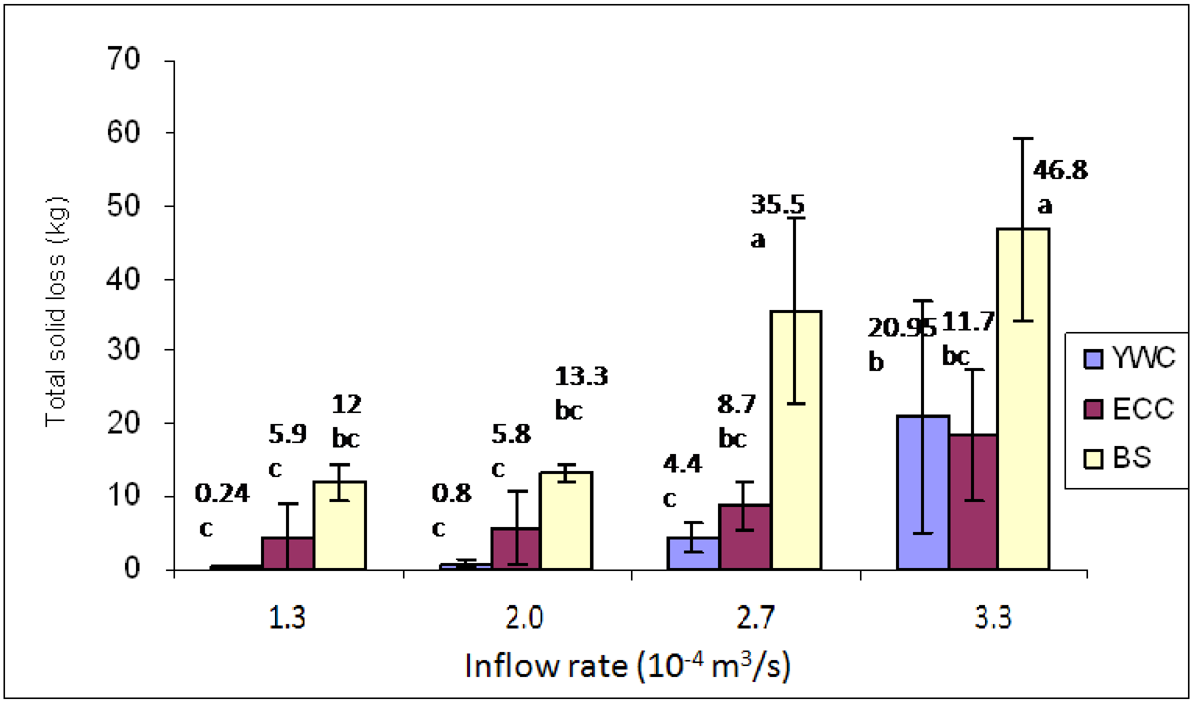

Figure 4.9. Mean and standard deviation of total solids loss from the three plots under four inflow rates (n =21 for each measurement).

CHAPTER 5

SOLIDS LOSS FORMULATION FOR COMPOST UNDER CONCENTRATED FLOW [3]

[3]Zhu, X., L. M. Risse, S. McCutcheon, B. Tollner, T. C. Rasmussen. To be submitted to *J. Environmental Engineering*

Abstract

While numerous *ad hoc* observations and a few formal investigations confirmed the effectiveness of compost applied for soil erosion control under certain conditions, no method existed before this study to calculate or represent the solids loss. This study developed an empirical equation for solids loss due to concentrated flow, relating the compost loss to site conditions, flow intensity, and characteristics of the compost. The Buckingham PI Theorem of dimensional analysis of laboratory and field data resulted in a relationship between dimensionless compost loss to slope and dimensionless concentrated flow rate. The empirical equation represented the solids loss from the yard waste compost ($r^2 = 0.73$, probability < 0.05) and erosion control compost ($r^2 = 0.64$, probability < 0.05) on laboratory and field plots better than the shear stress equation for soil erosion, primarily due to the uncertainty in estimating shear stresses.

Introduction

A compost blanket is a layer loosely applied on the soil surface to control erosion and retain sediment (USEPA, 2006). While the ultimate goal of applying compost is to prevent soil erosion, no one seems to have explicitly defined the performance and effectiveness of this practice. The loss of compose can result from erosion by raindrop impact and sheet flow, but the greatest erosion occurs when flow concentrates on the blanket, forming a rill that quickly erodes to the bottom of the typical 5-cm-deep blanket (recommended by USEPA, 2006). Figure 2.1 in this dissertation provides a typical example of an observed rill caused by concentrated flow. Investigators studying compost for erosion control have focused on the general performance of blankets applied heuristically (Claassen, 2000; Faucette *et al.*, 2004; Mukhtar *et al.*, 2004; Faucette *et al.*, 2007). Thus, little insight into the physical process of compost erosion and blanket failure resulted from these heuristic applications. An exception was Zhu and Risse (2009), who reported the limits of the shear stress equation for soil erosion to estimate solids loss from compost. The most important disadvantage of using the calibrated shear stress equation to estimate solids loss from compost blankets was the difficulty in accurately estimating shear stress acting on compost particles when micro-dams formed and truncate rill erosion.

Adopting the concept of watershed sediment yield from soil erosion was useful to evaluate the process of solids loss from compost. More useful than the amount of compost lost from a blanket as defined as the amount of compost reaching or passing a point of interest such as the downstream edge of the blanket or a watershed outlet in a given period, was the dimensionless loss relatable to concentrated flow. The objective of this study was to develop an equation that relates the solids loss from a compost blanket to the slope and path length, characteristics of compost, and intensity of concentrated flow. To achieve this objective, this investigation derived a relationship between dimensionless solids loss from compost with slope and dimensionless concentrated flow using laboratory and field data. As a result, this investigation was an important first step in understanding compost rill erosion and blanket failure.

Methodology

Compost Erosion Parameters

This study related compost loss to (1) kinetic and dynamic characteristics of the flow, (2) site conditions, and (3) compost characteristics. Similar to soil particles, compost undergoes erosion, entrainment, transport, and deposition (Merritt *et al.*, 2003). As the critical erosive state occurs after rainfall and the initial runoff saturates the surface, the laboratory tests in this study focused on concentrated flow over loosely applied, saturated compost. This critical erosion condition ends with compost failure defined by a rill deepening to the bottom of the compost blanket and causing erosion of soil underneath the blanket. This study hypothesized that concentrated flow affects loosely applied compost particles similar to noncohesive particles. A compost particle was generalized for this initial investigation as spherical (particle length, depth, and width were represented by one characteristic length scale, an equivalent diameter). Future studies may need to include a particle shape factor or measures of particle size distributions, and effects of particle cohesion to better estimate compost erosion.

Figure 5.1 illustrates the critical forces acting on a typical or critical compost particle with a length scale of the equivalent diameter d corrected for fibrous or nonspherical effects by the shape factor. The important forces acting on a typical particle included the drag force F_D, lift force F_L, resistance force F_R, and submerged particle weight W_s, all of which must include the effect of slope steepness S on the incipient motion of a representative noncohesive compost particle. Both the drag force F_D and the lift force F_L were exerted by concentrated flow and depend on the local velocity V_d that can be related to the mean flow velocity V for uniform, steady flows using the universal velocity distribution for boundary layer flows or an appropriate velocity profile for sediment stratified flows (McCutcheon, 1979) . The average velocity V was preferred for this analysis because this velocity scale was easier to measure or estimate (from discharge and area as $Q = VA$) than the local velocity V_d that is rarely measurable in field settings.

The local shear stress τ exerted by sheet or concentrated flow was expected to be the dominate force entraining compost particles. The relationship between the average shear stress τ[M L^{-1} T^{-2}] acting on the wetted perimeter W_p and the hydraulic radius R [L] is $\tau = \gamma RS$ where γ is the specific weight of water [M L^{-2} T^{2}] and S is the slope of the energy gradient. The hydraulic radius $R = A/W_p$ Both the wetted perimeter W_p [L] and cross-section area A [L^2] depended on the depth and width of flow in a rill. Therefore, shear stress, flow depth, and width of a rill are included in the set of important variables (Table 5.1).

According to Yalin (1977), the critical shear stress at which the particle will commence movement is proportional to the difference in specific weight between sediment and the fluid ($\gamma_s - \gamma_f$). Therefore, this analysis of variables took the difference in density between a compost particle and fluid ($\rho_s - \rho_f$) as one of the variables affecting the initiation of erosion. Converting the submerged weight to mass required the acceleration of gravity g to be included in the list of important variables.

Faucette *et al.* (2007) found that particle size was an important compost parameter that affected solids loss and runoff. This initial analysis represented the particle size of compost using the median particle size d_{50} of which 50 percent of the material is finer, with the use of the shape factor to modify an equivalent length scale appropriate for fibrous and other nonspherical particles. The shape factor S_p of compost particle was obtained using the Corey equation S_p = $c(ab)^{10.5}$ where a, b, and c are the length of the longest, the intermediate, and the shortest mutually perpendicular particle axes, respectively (Yang, 1996).

The depth of the compost was taken to be uniformly applied at 5 cm following the national fuidance for erosion control compost blanket (Alexander, 2003). Thus, this study did not select the depth of compost as an important variable in this study, although this parameter is very important in defining the failure of a compost blanket.

For this analysis, all of the chemical properties but one were assumed uniformed and consistent with the specifications of compost (USEPA, 1997). The only variable chemical property of compost was the organic matter content *OM*. The organic matter in compost, usually in the form of water-absorbing humus, dramatically affects the submerged weight of the compost particles. Thus, organic matter was an important soil characteristic in this analysis.

Transport of Compost Particles

The critical parameters for sediment transport include the critical shear velocity, critical boundary shear stress, or threshold mean current velocity (Roux, 2005). Sediment transport usually includes arbitrary definitions of bed load and suspended load. Graf (1971), Yalin (1977), Yang (1996), and Merritt *et al*. (2003) noted the numerous equations for bed load and suspended load transport. All of these equations focus on the skin friction, *i.e*., local shear stress exerted on the granular bed surface at a particular point.

Schiettecatte *et al*. (2008) reported that both detachment capacity and transport capacity of overland flow was strongly related to the total loss of solids. Therefore, this analysis included the total amount of transported particles q [M T^{-1}] and the overland flow rate or runoff discharge Q [L^3 T^{-1}] from a rill formed in the compost. The effective flow depth d [L] and flow width of a rill were also important in the transport of the compost particles as these factors were related to the bed shear (turbulent shear) and flow pattern.

Porosity of the compost p determines the amount of water that can infiltrates into the compost and the potential for subsurface flow. Significant infiltration decreases the amounts of water flowing on the surface of compost, resulting in reduced transport capacity.

According to Truman *et al.* (2001), the gross yield or delivery of compost particles was affected by slope length L and steepness S. Thus, slope length or flow path was included as an important variable.

Feasibility of Important Variables

Table 5.1 tabulates all these important variables discussed above. Before this study used these variables conduct a dimensional analysis, the Buckingham PI Theorem required a check of independence. The check of independence for the important variables reduced the list in Table 5.1 by removing obvious redundancies. Firstly, Table 5.2 dropped velocity as redundant with runoff or concentrated flow rate *Q*. Secondly, rill flow depth and width also depended upon the concentrated flow rate, thus this analysis dropped these variables in favor of the ease of making flow measurements. Thirdly, because particle size and shape partially influence the porosity of compost, Table 5.2 dropped the shape factor. Finally, this analysis dropped organic matter content of compost particles, as partially defined by submerged density or buoyancy. Ignoring organic content is consistent with ignoring particle cohesion in this initial analysis. Overall, this reasoning reduced the number of important variables to seven, as listed in Table 5.2.

This study checked the importance of the variables in Table 5.2 by comparison to the parameters in the universal soil loss equation and the Water Erosion Prediction Project equation. The universal soil loss equation was defined as (Troeh *et al.*, 1999)

$$A = R\ K\ LS\ C\ P \qquad (1)$$

where

A = estimated average annual soil loss

R = rainfall and runoff factor

K = soil erodibility factor

LS = slope length and steepness factor

C = cover management factor

P = supporting practice factor

The Water Erosion Prediction Project equation was defined as (Elliot *et al.*, 1989)

$$D_c = -\frac{T_c}{W_r L} ln\left\{1 - \left(\frac{Q_s}{W_r T_c}\right)\left(\frac{D_c'}{D_c' + E)}\right)\right\} \qquad (2)$$

where

$$D_c' = k(\tau - \tau_c) \quad (3)$$

$$\tau = \gamma RS$$

$$\gamma = g\,\rho$$

Dc = detachment capacity

D_c'= detachment capacity of clean water

K = soil erodibility

τ = shear stress

γ = specific weight of the flowing fluid

g = acceleration of gravity

ρ = fluid density

L = rill length

W_r = rill channel width

T_c = transport capacity along a rill

Q_s = sediment delivery rate from a rill

E = interrill contribution to erosion

Among the selected important variables for solids loss from compost blankets, the universal soil loss equation (2) and Water Erosion Prediction Project equation (3) contain slope *S*, slope or path length *L*, concentrated flow rate *Q* as an erosive agent, gravity *g*, and fluid density ρ. The soil erodibility factor used in equations (2) and (3) is a soil property.

Dimensionless Groups

From Table 5.2, the empirical equation describing the solids loss from compost under concentrated flow was

$$q = f\ (L, Q, d_{50}, \rho_s - \rho_f\ , g, S) \quad (4)$$

For the seven important variables and three basic dimensions of mass [M], length [L], and time [T], the Buckingham Π Theorem produced 7 – 3 = 4 dimensionless and independent groups to describe compost loss due to concentrated flow. The slope length *L*, runoff rate *Q*, and difference in density between compost particle and fluid ($\rho_s - \rho_f$) were chosen as primary variables to represent the three dimensions because these three variables could not form a dimensionless group (Murphy, 1950).

Dimensionless PI terms are formed by conducting dimensional analysis using Gauss-Jordan elimination (Wikipedia, 2008) on the dimensional matrix. The procedure followed was

1. Tabulation of the important variables and the associated dimensions in a dimensional matrix as show in Table 5.3

2. The dimension of length [L] in the matrix was systematically eliminated using the primary variable slope length *L* to form the products in Table 5.4 (by multiplication of selected variables with the length scales [L^{-3}], [L^{-1}], or [L^{3}], resulting in all zeros in the column of dimension [L])

3. The dimension of time [T] was eliminated from Table 5.4 by multiplying the selected terms by $Q^{-1} L^3$ and $Q^{-2} L^6$ to form the products shown in Table 5.5, which results in all zeros in the column of dimension [T]

4. The dimension mass [M] was eliminated by multiplying the necessary quantities by

   $(\rho_s - \rho_f)^{-1} L^{-3}$, resulting in all zeros in the column of dimension [M] in Table 5.6

The four dimensionless groups remaining in Table 5.6 are the four independent dimensionless ∏ terms expected

$$\prod_1 = \frac{qL^2}{Q(\rho_s - \rho_f)} \quad (5)$$

$$\prod_2 = \frac{d_{50}}{L} \quad (6)$$

$$\prod_3 = \frac{L^5 g}{Q^2} \quad (7)$$

$$\prod_4 = S \quad (8)$$

Therefore, the solids loss from compost blankets was

$$F\left(\frac{qL^2}{Q(\rho_s - \rho_f)}, \frac{d_{50}}{L}, \frac{L^5 g}{Q^2}, S\right) = 0 \quad (9)$$

or

$$\frac{qL^2}{Q(\rho_s - \rho_f)} = F\left(\frac{d_{50}}{L}, \frac{L^5 g}{Q^2}, S\right) \quad (10)$$

Dimensionless Compost Yield Equation

While the Buckingham PI Theorem produces $\prod$ terms which are important groups of pertinent variables, a relationship among those $\prod$ terms must be established from analysis of experimental data (Murphy, 1950), including regression analysis. This study used the laboratory data for erosion of yard waste compost reported in this dissertation (Chapter 3) to develop an empirical equation representing the solids loss from a compost blanket. As the median particle diameter was approximately constant for one single type of compost and the slope length was fixed in the study, the constant dimensionless group of $\frac{d_{50}}{L}$ was dropped from the list of $\prod$ terms (Murphy, 1950). Table 5.7 provided the ranges of the measured important variables and dimensionless $\prod$ terms for the laboratory study. Regression was conducted to form component equations of $\prod_1$ *versus* $\prod_2$ with a fixed value of $\prod_3$, and of $\prod_1$ *versus* $\prod_3$ with a fixed value of $\prod_2$. Table 5.8 listed the resulting equations and corresponding coefficient of determinations r^2. See Figures 5.2 and Figure 5.3. According to Murphy (1950), the relationships between $\prod_1$ and the other individual $\prod$ terms can be combined to form an empirical relation by multiplication or addition under certain conditions. The empirical equation formed by addition was

$$\Pi_1 = F(\Pi_2, \overline{\Pi_3}) + F(\overline{\Pi_2}, \Pi_3) - F(\overline{\Pi_2}, \overline{\Pi_3}) \qquad (11)$$

given that the condition

$$F(\Pi_2, \overline{\Pi_3}) - F(\overline{\Pi_2}, \overline{\Pi_3}) = F(\Pi_2, \overline{\overline{\Pi_3}}) - F(\overline{\Pi_2}, \overline{\overline{\Pi_3}}) \qquad (12)$$

is satisfied. The over bar denotes constant values of $\prod$ terms; the term $\overline{\overline{\Pi_3}}$ denotes a constant value that differs from $\overline{\Pi_3}$.

Results and Discussion

Trial and error led to the empirical equation formed by addition

$$\Pi_1 = a + b\,\Pi_2 + c\,\Pi_3 \qquad (13)$$

Values of a, b, and c were determined following the method described by Murphy (1950). The functions F(Π_2, $\overline{\Pi_3}$) and F(Π_2, $\overline{\overline{\Pi_3}}$) were selected arbitrarily from Table 5.8 as

$$\Pi_1 = 9E\text{-}12\,\Pi_2 + 0.1477 \qquad (14)$$

$$\Pi_1 = 9E\text{-}12\,\Pi_2 + 0.2980 \qquad (15)$$

For $\overline{\Pi_3} = 0.03$ and $\overline{\overline{\Pi_3}} = 0.07$ used in the arbitrarily selected component equation from Table 5.8, $\Pi_1 = 3.7025\,\Pi_3 - 0.0186$, the constant value was

$$F(\overline{\Pi_2}, \overline{\Pi_3}) = 0.0924 \qquad (16)$$

and

$$F(\overline{\Pi_2}, \overline{\overline{\Pi_3}}) = 0.2404 \qquad (17)$$

Plugging equations (14), (15), (16), and (17) into the left hand and right hand sides of equation (12) resulted in

Left hand side of equation (12): 9E-12 Π_2 + 0.0553 (18)

Right hand side of equation (12): 9E-12 Π_2 + 0.0576 (19)

Given the range of Π_2 is 4.1E8 to 7.73E13 (Table 5.7), equation (18) and equation (19) were taken as approximately equal. This test established that addition was appropriate to form an equation. Therefore, the formula for compost loss under concentrated flow conditions was

$$\frac{qL^2}{(\rho_s - \rho_f)Q} = a + bS + c\frac{\mathrm{g}\mathrm{L}^5}{\mathrm{Q}^2} \qquad (20)$$

where

a, *b*, and *c* = dimensionless empirical coefficients determined using experimental data

Equation (20) fit to the laboratory data for 1 percent, 3 percent, 5 percent, and 7 percent slopes reported by Zhu *et al.* (2009) by multiple regression of $\frac{qL^2}{(\rho_s - \rho_f)Q}$ *versus* S and $\frac{\mathrm{g}\mathrm{L}^5}{\mathrm{Q}^2}$. The correlation was r^2 = 0.71 (Table 5.9, F = 2.06E-12), a better representation of solids loss form compost compared to the shear stress equation (Table 3.3 F = 0.176, r^2 = 0.03, and Table 3.4 F = 0.0011, r^2 = 0.12) .

To determine the reliability of the equation (20), field data by Zhu and Risse (2009) were used to compute the values of the Π terms. Due to the constant slope of 0.125 selected by Zhu and Risse (2009), the relationship between $\frac{qL^2}{(\rho_s - \rho_f)Q}$ and $\frac{gL^5}{Q^2}$ for yard waste compost and erosion control compost, respectively, were found using regression. The equation for solids loss from yard waste compost under concentrated flows was

$$\frac{qL^2}{(\rho_s - \rho_f)Q} = 1.28 - 1.73\text{E-}14\,\frac{\text{gL}^5}{\text{Q}^2} \qquad (21)$$

The equation for erosion control compost was

$$\frac{qL^2}{(\rho_s - \rho_f)Q} = 12.09 - 1.63\text{E-}13\,\frac{\text{gL}^5}{\text{Q}^2} \qquad (22)$$

The equation derived from the laboratory data provided a significant fit to the field data (Zhu and Risse, 2009). As shown in Table 5.10, the significant F = 0.0004, r^2=0.73 for yard waste compost and F = 0.0017, r^2=0.64 for erosion control compost. The negative coefficients (slope) in the equations established a reduction of solids loss with increased $\frac{\text{gL}^5}{\text{Q}^2}$, achievable by increasing slope length or reducing the rate of concentrated flow. This result was also consistent with the reported phenomenon of micro-dam formation in compost rills that blocked flow and sediment transport (Zhu and Risse 2009).

Discrepancies in laboratory and field coefficients were due to

1. The flume for which the laboratory equation was developed had a hard bed that prevented any further down cutting yield of solids
2. Both the flow length and slope in the field exceeded the ranges of the corresponding laboratory values used to form the initial equation
3. This investigation dropped one of the original Π terms, $d_{50}\,Q^{-1}$, to form the laboratory equation, resulting in reduced sensitivity to compost properties

Summary and Conclusions

Insight into the physical process and careful analysis of compost erosion led this investigation to select dimensionless groups of important variables using the Buckingham PI

Theorem. These dimensionless groups were used with the laboratory data to form an empirical equation to describe solids loss from compost blankets. The empirical equation provided a better description for solids loss from yard waste compost subjected to concentrated flow in the laboratory. The empirical equation also better described the relationship between dimensionless solids loss and dimensionless concentrated flow rate for both yard waste compost and erosion control compost under field conditions. Application of the dimensionless groups to form an equation for compost erosion avoided blind regression analysis and covered the effects of micro-dams for the first time.

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Table 5.1 Initial list of important variables pertaining to solids loss from compost

No.	Variable	Symbol	Units	Dimensions
1	Compost yield	q	kg s^{-1}	M T^{-1}
2	Shear stress	τ	kg m^{-1} s^{-2}	M L^{-1} T^{-2}
3	Slope	S	-	Dimensionless
4	Flow path length	L	m	L
5	Concentrated flow rate	Q	m^3 s^{-1}	L^3 T^{-1}
6	Median particle size	d_{50}	m	L
7	Particle buoyancy or difference in density between particles and fluid	$(\rho_s - \rho_f)$	kg m^{-3}	M L^{-3}
8	Mean flow velocity	V	m s^{-1}	L T^{-1}
9	Flow depth in rills	d	m	L
10	Flow width in rills	w	m	L
11	Porosity of compost	p	-	Dimensionless
12	Particle shape factor	Ps	-	Dimensionless
13	Acceleration of gravity	g	m s^{-2}	L T^{-2}
14	Organic matter content	OM	-	Dimensionless

Table 5.2 Revised pertinent variables for solids loss on compost under concentrated flow.

No.	Variables	Symbol	Units	Dimensions
1	Compost yield	q	g m^{-2} s^{-1}	$L^{-2}M$ T^{-1}
2	Slope length	L	m	L
3	Inflow rate	Q	m^3 s^{-1}	L^3 T^{-1}
4	Median particle size	d_{50}	m	L
5	Buoyancy or difference in density between sediment and fluid	$(\rho_s - \rho_f)$	kg m^{-3}	M L^{-3}
6	The acceleration of gravity	g	m s^{-2}	L T^{-2}
7	Slope steepness	S	-	Dimensionless

Table 5.3 Dimensional matrix for important variables

Quantities	Dimensions		
	L	M	T
q	-2	1	-1
Q	3	0	-1
L	1	0	0
d_{50}	1	0	0
$\rho_s - \rho_f$	-3	1	0
g	1	0	-2
S	0	0	0

Table 5.4 Elimination of the dimension length L

Quantities	Dimensions		
	L	M	T
qL^2	0	1	-1
$Q L^{-3}$	0	0	-1
$L L^{-1} = 1$	0	0	0
$d_{50} L^{-1}$	0	0	0
$(\rho_s - \rho_f) L^3$	0	1	0
$g L^{-1}$	0	0	-2
S	0	0	0

Table 5.5 Elimination of the dimension time T

Quantities	Dimensions		
	L	M	T
$q\ L^5\ Q^{-1}$	0	1	0
1	0	0	0
1	0	0	0
$d_{50}\ L^{-1}$	0	0	0
$(\rho_s - \rho_f)\ L^3$	0	1	0
$g\ L^5\ Q^{-2}$	0	0	0
S	0	0	0

Table 5.6 Elimination of the dimension mass M

Quantities	Dimensions		
	L	M	T
$q\,L^2Q^{-1}\,(\rho_s - \rho_f\,)^{-1}$	0	0	0
1	0	0	0
1	0	0	0
$d_{50}\,L^{-1}$	0	0	0
1	0	0	0
$g\,L^5\,Q^{-2}$	0	0	0
S	0	0	0

Table 5.7 Ranges of measured variables and $\prod$ terms using laboratory study data.

Variables	Laboratory ranges
Particles loss: q, gm^{-1} s^{-1}	0.056 to 8.28
Concentrated flow rate: Q, m^3 s^{-1}	0.0001 to 0.0013
Slope: S, dimensionless	0.01 to 0.07
Flow path length: L, m	3
Particle size: d_{50} , m	9.7E-4
Difference of density between sediment and water or buoyancy force: $(\rho_s - \rho_f)$, kg m^{-3}	283.8
$\prod$ Terms	**Ranges**
$\prod_1 = q\, L^2\, (\rho_s - \rho_f)^{-1}\, Q^{-1}$	1.56E-4 to 1.12
$\prod_2 = \frac{L^5 g}{Q^2}$	4.1E8 to 7.73E13
$\prod_3 = S$	0.01 to 0.07

Note: L and $(\rho_s - \rho_f)$ were constant for yard waste compost.

Table 5.8 Component equations derived from the laboratory study data (Zhu *et al.*, 2009)

Variables	PI terms	Component equations	Correction coefficient
Q, $m^3 s^{-1}$	$L^5 g Q^{-2}$	$\Pi_1 = F(\overline{\Pi_2}, \Pi_3)$	r^2
0.1E-3	4.03E10	$\Pi_1 = 7.2452\,\Pi_3 - 0.1249$	0.84
3.5E-4	7.19E9	$\Pi_1 = 3.7025\,\Pi_3 - 0.0186$	0.97
0.7E-3	1.30E9	$\Pi_1 = 2.7535\,\Pi_3 - 0.0471$	0.91
1.3E-3	7.19E8	$\Pi_1 = 23.909\,\Pi_3 - 0.042$	0.91
S	*S*	$\Pi_1 = F(\Pi_2, \overline{\Pi_3})$	r^2
0.01	0.01	$\Pi_1 = (2E\text{-}13)\,\Pi_2 + 0.0862$	0.69
0.03	0.03	$\Pi_1 = (9E\text{-}12)\,\Pi_2 + 0.1477$	0.74
0.05	0.05	$\Pi_1 = (1E\text{-}11)\,\Pi_2 + 0.1557$	0.79
0.07	0.07	$\Pi_1 = (9E\text{-}12)\,\Pi_2 + 0.2980$	0.67

Table 5.9 Result of multiple regression analysis of $\frac{qL^2}{(\rho_s - \rho_f)Q}$ *versus* S and $\frac{\mathrm{gL}^5}{\mathrm{Q}^2}$, using data lumped from 4 slopes as reported by Zhu *et al.* (2009).

	Coefficients	Standard Error	t Stat	Probability	Significant F	r^2
Intercept	-0.119	0.062	-1.917	0.062		
$\frac{\mathrm{gL}^5}{\mathrm{Q}^2}$	8.57E-12	1.03E-12	8.343	1.55E-10	2.06E-12	0.71
S	5.880	1.249	4.707	0.000		

Table 5.10 Regression analysis of $\frac{qL^2}{(\rho_s - \rho_f)Q}$ and $\frac{gL^5}{Q^2}$ using data from Zhu and Risse (2009).

Compost		Coefficients	Probability	Significant F	r^2
Yard waste	Intercept	12.09	4.66E-06	0.0004	0.73
	$\frac{gL^5}{Q^2}$	-1.63E-13	0.000		
Erosion control compost	Intercept	1.28	3.18E-05	0.0017	0.64
	$\frac{gL^5}{Q^2}$	-1.73E-14	0.002		

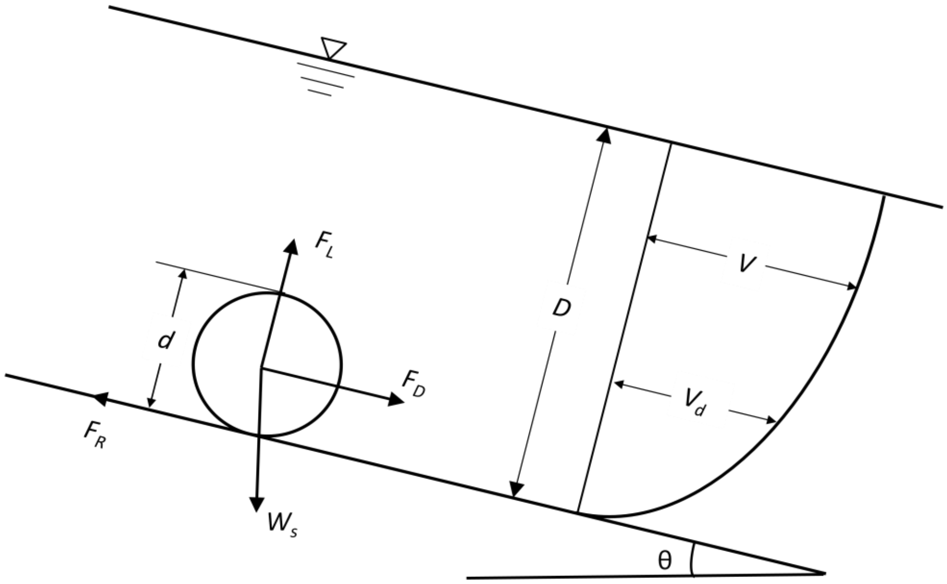

Figure 5.1 Response of a noncohesive compost particle to concentrated flow.

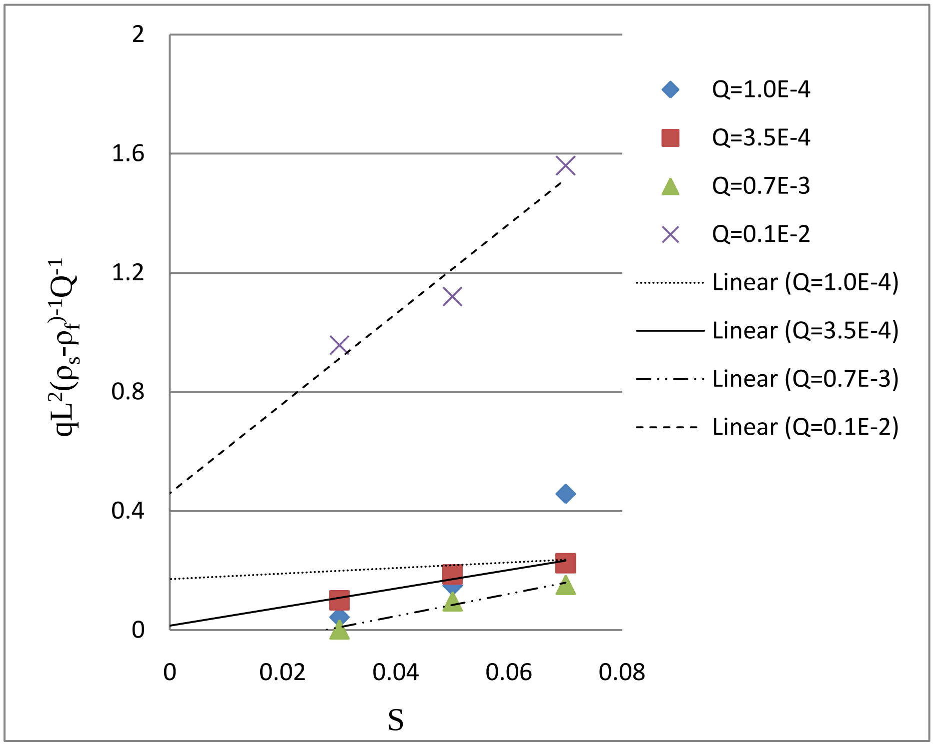

Figure 5.2 Relationship between dimensionless compost yield, $q\ L^2\ (\rho_s\text{-}\rho_f)^{-1}\ Q^{-1}$, and slope, S, under four consequentially increased concentrated flow rates. (Units of Q: $m^3\ s^{-1}$)

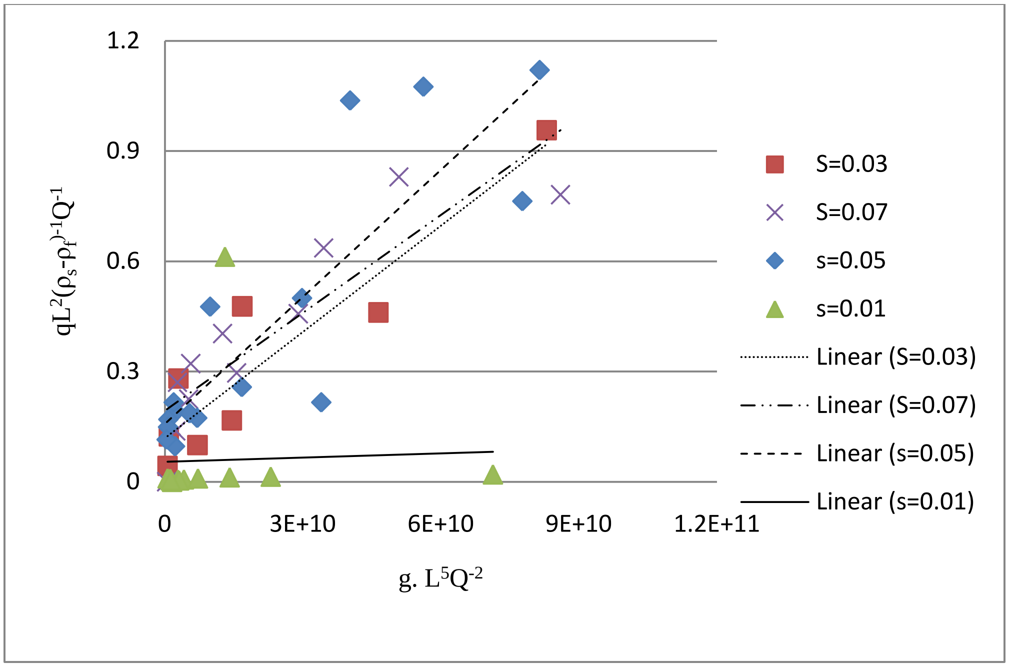

Figure 5.3 Relationship between dimensionless compost yield, $q\ L^2\ (\rho_s\text{-}\rho_f)^{-1}\ Q^{-1}$, and, $g\ L^5\ Q^{-2}$**,** for four different slopes. (Data source: Laboratory study by Zhu *et al*., 2009)

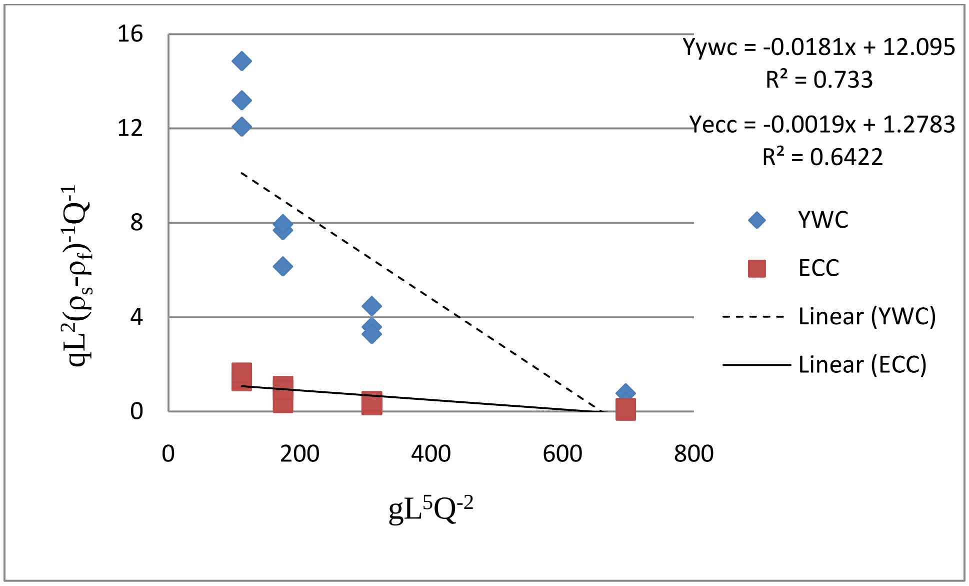

Figure 5.4 Relation between dimensionless compost erosion $\frac{qL^2}{(\rho_s - \rho_f)Q}$ and $\frac{gL^5}{Q^2}$, using data from Zhu and Risse (2009); YWC: yard waste compost; ECC: Erosion control compost.

CHAPTER 6

CONCLUSIONS

This investigation reported on laboratory and field studies that resulted in the development of an equation for the solids loss from compost subjected to concentrated flows. In the laboratory, this study subjected two composts and a control Cecil soil to four sequentially increased concentrated flows in a flume tilted to four different slopes. This laboratory study used erosion yields and calculated mean shear stresses to evaluate the shear stress equation for rill erosion of soil. The field study investigated the effectiveness of two types of composts in reducing soil erosion caused by concentrated flow. The investigation evaluated rill development on two types of compost subjected to concentrated flow. Both studies used the predominant soils near the locations as controls that defined how much soil erosion the compost applications prevented.

The major findings and conclusions were:

- The erosion of yard waste compost measured in the laboratory minimally conformed to the shear stress equation first proposed by DuBoys in 1879, as did the Cecil soil control. Yet, rill erosion in compost and soil evolved very differently—soil head cutting to form broader rills from the downstream most edge *versus* down cutting of narrower compost rills from the upstream edge. Critical shear stresses for the Cecil soil control and yard waste compost measured in the laboratory were not significant different, but the empirical erodibility coefficient was significantly less for the yard waste compost than for the Cecil soil. Among the materials tested in the laboratory, erosion control compost performed best in reducing solids loss. However, the shear stress equation could not be represent the solids loss from erosion control compost primarily because the formation of micro-dams on the compost resulted in difficulty estimating the shears stress acting on the compost.

- Over the limited laboratory and field conditions investigated, formation of micro-dams on erosion control compost was a key mechanism preventing rill erosion by concentrated flow. The yard waste compost applied in the field also formed micro-dams under concentrated flow. This study seems to be the first to make systematic observations of micro-dam flow blockage despite some heuristic observations of rill blockage in field settings. The occurrence of these nonuniform flows prevented adequate estimates of shear stresses and did not allow testing of the applicability of the shear stress equation to describe loss of compost. Yet, the micro-dam particle trapping, reduction of flow velocities, and resulting lateral flow and noticeable infiltration were all important mechanisms by which compost reduces erosion.
- This study developed a regression equation of dimensionless groups derived using the Buckingham PI Theorem to describe the limited laboratory and field plot observations of compost loss due to concentrated flow. The regression equation better represented the solids loss from yard waste compost in the laboratory setting compared to the shear stress equation, and allowed representation of solids loss from both yard waste compost and erosion control compost in the field, which could not be represented using the shear stress equation.

This analysis provided tentative definition of important dimensionless groups that may lead to a more generalized equation. The long-term goal to develop a computerized tool that allows erosion control engineers to select the most suitable erosion control compost under specific site conditions requires

1. Further investigation of solids loss from field application of compost, including the following:

a. Additional study should consider at least five types of commonly used erosion control compost to investigate more broadly the effects of compost characteristics on erosion. Follow-up studies must reexamine the particle size distribution, shape factor, and organic matter content as important variables. Most important is the need to investigate the heuristically derived 5-cm depth of compost applications to determine is deeper applications on steeper slopes is feasible to defer blanket failure caused by down cutting.
b. Further study also needs to investigate extended ranges of slope and slope or flow path length. The range of slopes should cover from 1 percent to 33.3 percent, the typical steepness of highway right-of-way embankments on which design engineers normally use compost to prevent erosion.
c. Additional field studies could use simulated rainfall of different intensities and concentrated flows to confirm critical erosion scenarios defined in this investigation.
d. Other studies could test various underlying soil structures to define any effect on solids loss from compost.

2. A more generalized regression equation or an optimized semi-empirical model based on MATLAB™ or other software, using more extensive field data to represent the solids loss from all commonly used erosion control composts, is necessary.
3. Efforts are also necessary to embed or adapt these results into soil erosion descriptors such as the Revised Universal Soil Loss Equation and the Water Erosion Prediction Project equation.